National Library of Canada
Bibliothèque nationale du Canada

Canadian Theses Service
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

NL-339 (r. 88/04) c

Canada

UNIVERSITY OF ALBERTA

DIAGENETIC ALTERATION OF *STROMBUS GIGAS*, *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS* FROM THE PLEISTOCENE IRONSHORE FORMATION OF GRAND CAYMAN

by

JILL REHMAN

©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

SPRING 1992

National Library of Canada
Bibliothèque nationale du Canada

Canadian Theses Service
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-73111-7

Canada

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: **JILL REHMAN**

TITLE OF THESIS: **DIAGENETIC ALTERATION OF *STROMBUS GIGAS*, *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS* FROM THE PLEISTOCENE IRONSHORE FORMATION OF GRAND CAYMAN**

DEGREE: **MASTER OF SCIENCE**

YEAR THIS DEGREE GRANTED: **SPRING 1992**

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as hereinbefore provided neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

Jill Rehman

#96 219 90 Avenue S.E.
Calgary, Alberta
T2J 0A3

April 24, 1992

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled DIAGENETIC ALTERATION OF *STROMBUS GIGAS*, *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS* FROM THE PLEISTOCENE IRONSHORE FORMATION OF GRAND CAYMAN submitted by JILL REHMAN in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

.....
Dr. B. Jones (Supervisor)

.....
Dr. B.D.E. Chatterton

.....
Dr. C. Stelck

.....
Dr. G. Evans

April 8, 1992

ABSTRACT

The Pleistocene Ironshore Formation has resided in the subaerial diagenetic realm, apart from brief periods in the marine and freshwater phreatic zones shortly after its deposition 125,000 years ago, and during the last 5,000 years. Meteoric diagenesis included aragonite to calcite alteration and calcite cementation. In *Strombus gigas*, *Siderastrea siderea*, and *Montastrea annularis* replacement of aragonite by calcite was controlled by skeletal structure and the distribution and amount of porosity.

Shells of *Strombus gigas*, formed of four layers of densely packed parallel rod-shaped aragonite crystals, are replaced to varying degrees by calcite. The morphology and distribution of calcite was controlled by interfaces between shell layers that now form planar to gently curving boundaries for the calcite crystals. Calcite crystals are tangentially oriented around sponge borings. Inclusions of relict aragonite crystals and disseminated organic matter preserve primary microstructure. *Siderastrea siderea* and *Montastrea annularis* are composed of a porous network of aragonitic trabeculae that are partly to totally replaced by calcite. In partly altered trabeculae, calcite crystals are situated along leached centers of calcification. In *Siderastrea siderea*, calcite crystals are based along synapticulothecae and extend along septa into adjacent calices. In *Montastrea annularis*, less dense growth layers are preferentially replaced relative to more dense layers.

Calcitization of *Strombus gigas* occurred by *in situ* dissolution of aragonite and reprecipitation of calcite (neomorphism) along a migrating diagenetic front. The front, which proceeded into the shell from its outer edge and sites of secondary porosity, was temporarily dammed along organic rich contacts between shell layers. In *Siderastrea siderea* and *Montastrea annularis*, calcitization occurred by neomorphism and precipitation of calcite cement in dissolution cavities. In both cases, dissolution of aragonite and subsequent precipitation of calcite began along centers of trabeculae and proceeded outwards.

Neomorphic calcite in *Strombus gigas* contains curved to irregular zones, 5 to 10 μm wide, that are akin to zones in calcite cements described from carbonates throughout the geologic column. Neomorphic products are distinguished from cements because they consist of irregularly-shaped, pleochroic crystals with undulose extinction, non-planar intercrystalline and intracrystalline boundaries and rare enfacial junctions.

ACKNOWLEDGEMENTS

I am indebted to Dr. Brian Jones for his guidance, supervision, and expert editorial skills which have greatly improved this thesis. I would also like to thank my fellow graduate students, particularly Ian Hunter and Rob MacDonald for their suggestions, discussions and assistance during the course of this study. I also greatly appreciate the assistance provided by Elsie Tsang.

Assistance in the field was kindly provided by Ian Hunter, Sarah Cerridwen, Sam Ng and Brian Jones. I am grateful to George Braybrook, who took many of the SEM photographs, and to Barb Stenz, who mounted the photographic plates.

The research was funded by the Natural Science and Engineering Research Council of Canada (NSERC Grant A6090 to Jones). Accommodation on Grand Cayman was provided by the Mosquito Research and Control Unit.

I would like to thank my examination committee, Dr. Chatterton, Dr. Stelck, and Dr. Evans for their consideration and approval of this thesis.

Finally, I wish to express my sincere thanks to my family and friends for their encouragement and support throughout the course of this research.

TABLE OF CONTENTS

Chapter **Page**

I. INTRODUCTION 1

A. LATE PLEISTOCENE PALEOGEOGRAPHY AND SEDIMENTOLOGY 3

B. OBJECTIVES 7

C. METHODS 7

D. OCCURRENCE OF *STROMBUS GIGAS*, *SIDERASTREA SIDEREA*, AND *MONTASTREA ANNULARIS* 11

E. TERMINOLOGY 13

F. TEXTURAL CRITERIA FOR THE RECOGNITION OF CEMENT AND NEOMORPHIC SPAR 15

II. SKELETAL MORPHOLOGY AND STRUCTURE 17

A. *STROMBUS GIGAS* 17

Shell Morphology 17

Skeletal Microstructure 20

B. *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS* 20

Skeletal Morphology 20

Siderastrea siderea 20

Montastrea annularis 22

Skeletal Microstructure 23

Siderastrea siderea 26

Montastrea annularis 26

III. DIAGENETIC ALTERATION OF *STROMBUS GIGAS* 28
A. SPONGE BORINGS 28
Morphology and Distribution 28
Internal Sediments.....33
Composition and Distribution 33
Grain Size and Sorting 35
Cements 35
Blocky Calcite Spar 36
Pelsparite 36
Micrite Coatings 37
Needle Fibre Calcite 37
Discussion.....38
Origin and Occurrence of Sponge Borings 38
Composition, Grain Size and Sorting of Internal Sediments ..40
Origin of Cements 40
Blocky Calcite Spar 42
Pelsparite 42
Micrite Coatings 44
Needle Fibre Calcite 46
Cement Distribution 47
B. MINERALOGICAL ALTERATION OF THE SHELL.....48
Textural and Mineralogical Relationships 48
Evidence for a Neomorphic Origin of Calcite 58
C. DIAGENETIC MODEL.....59
Aragonite to Calcite Inversion 59
Controls on Diagenesis 65

IV. DIAGENETIC ALTERATION OF *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS* 66

A. DIAGENETIC ALTERATION 66

Siderastrea siderea 66

Zone I 69

Zone II 69

Zone III 74

Zone IV 75

Zone V 75

Montastrea annularis 76

Zone I 77

Zone II 77

Zone III 84

Zone IV 84

Internal Sediments 85

Borings 85

Root Borings 87

B. DISCUSSION 87

Aragonite Dissolution 87

Origin of Cements 91

Aragonite Needle Cement 91

Micrite Coatings 92

Pelsparite 92

Blocky Calcite Spar 93

Needle Fibre Calcite 94

C. DIAGENETIC MODEL 94

Mineralogical Alteration 96

Porosity and Permeability Changes 97

V. DISCUSSION 99

A. CONTROLS ON THE ALTERATION OF ARAGONITIC SKELETAL COMPONENTS TO CALCITE 100

Time 100

Climate 101

Facies 102

Skeletal Composition, Structure and Microstructure 103

Diagenetic Environment 105

B. SEA LEVEL HISTORY AND DIAGENESIS 107

C. USE OF TEXTURAL CRITERIA FOR DISTINGUISHING BETWEEN NEOMORPHIC SPAR AND CEMENT 112

D. SIGNIFICANCE OF GROWTH ZONES IN NEOMORPHIC CALCITE 114

VI. CONCLUSIONS 116

VII. REFERENCES 119

VIII. APPENDICES 134

A. SAMPLING LOCALITIES 134

B. FEIGL'S SOLUTION 136

LIST OF FIGURES

Figure		Page
I-1	Location map and geological map of Grand Cayman	2
I-2	Paleogeographic map of Grand Cayman	4
I-3	Map of Grand Cayman showing positions of Pleistocene localities relative to depositional environment and facies	6
I-4	Distribution of *Strombus gigas*, *Siderastrea siderea*, and *Montastrea annularis* in facies of the Ironshore Formation	12
II-1	Schematic diagram of crossed-lamellar structure	21
II-2	Schematic diagram of basic scleractinian microstructure	24
III-1	Tracings of serial sections of *Strombus gigas* showing the distribution of calcite and aragonite in three dimensions	32
III-2	Schematic diagram of typical sediment/cement distributions within sponge borings in *Strombus gigas*	34
III-3	Percentage boring in *Strombus gigas* for facies of the Ironshore Formation	39
III-4	Schematic diagram of possible cement sequences in sponge borings in *Strombus gigas*	41
III-5	Relative proportions of aragonite and calcite in *Strombus gigas* for facies of the Ironshore Formation	49
III-6	Summary of the diagenetic history of *Strombus gigas*	60
III-7	Schematic diagram of *in situ* dissolution/reprecipitation across a thin solution film	62
III-8	Ternary diagram of percentage boring versus percentage aragonite and calcite in *Strombus gigas*	63
IV-1	Diagenetic zones of *Siderastrea siderea*	70
IV-2	Diagenetic zones of *Montastrea annularis*	80
IV-3	Summary of the diagenetic history of *Siderastrea siderea* and *Montastrea annularis*	95
V-1	Pleistocene sea level changes and diagenetic history of the Ironshore Formation	109

LIST OF TABLES

Table		Page
I-1	Summary of lithology, fossils, and trace fossils of Ironshore facies	5
I-2	List of samples of *Strombus gigas*	8
I-3	List of samples of *Siderastrea siderea*	9
I-4	List of samples of *Montastrea annularis*	10
I-5	Textural criteria for the recognition of cement and neomorphic spar	16
III-1	List of thin sections of *Strombus gigas*	29
IV-1	Summary of the textural characteristics of diagenetic zones in *Siderastrea siderea*	71
IV-2	Summary of the textural characteristics of diagenetic zones in *Montastrea annularis*	81

LIST OF PLATES

Plate

II-1 Skeletal structure and microstructure of *Strombus gigas*, *Siderastrea siderea* and *Montastrea annularis* 19

III-1 Sponge borings, internal sediments and cements in *Strombus gigas* 31

III-2 Photograph of a thin section through the columella of *Strombus gigas* 51

III-3 Alteration of the aragonitic shell of *Strombus gigas* to calcite 53

III-4 Textural characteristics of the calcite mosaic in *Strombus gigas* 57

IV-1 Photograph of a thin section of *Siderastrea siderea* 68

IV-2 Diagenetic alteration of *Siderastrea siderea* 73

IV-3 Photograph of a thin section of *Montastrea annularis* 79

IV-4 Diagenetic alteration of *Montastrea annularis* 83

IV-5 Root borings, needle fibre calcite and aragonite dissolution in *Montastrea annularis* and *Siderastrea siderea* 89

I. INTRODUCTION

Grand Cayman is the largest of three Caribbean islands collectively known as the Cayman Islands (Figure I-1). Each island has a core of dolostone belonging to the Oligocene-Miocene Bluff Formation, that is unconformably overlain by Pleistocene limestones of the Ironshore Formation (Matley 1926; Brunt *et al.* 1973; Jones and Smith 1988; Jones and Hunter 1989).

The Ironshore Formation comprises wackestones, packstones, grainstones floatstones, boundstones, and rudstones deposited in a variety of relatively shallow water environments (Hunter and Jones 1988, 1989). These limestones contain a diverse assemblage of corals, gastropods, bivalves and foraminifera, along with non-skeletal allochems such as ooids and lithoclasts.

The diagenetic history of the Ironshore Formation is relatively simple in comparison to the complex, multiphase history of the Bluff Formation (Jones and Hunter 1989, Ng 1990). Diagenetic changes occurred in the submarine and meteoric environments. Submarine alteration of limestones in the Ironshore Formation took place via inorganic and biologically controlled cement precipitation, bioerosion, mechanical erosion, and resedimentation. With eustatic sea level change, submarine diagenetic processes gave way to meteoric diagenesis, which involved dissolution, cementation, and replacement of aragonitic skeletal and non-skeletal components by calcite.

The mineralogical alteration of skeletal components from aragonite to calcite is a significant aspect of diagenetic alteration in the Ironshore Formation limestones. The replacement of aragonite by calcite in the meteoric environment occurs in response to the instability of aragonite at normal surface temperatures and pressures (Jamieson 1953; Clark 1957; Fyfe and Bischoff 1965). Mineralogical change takes place either by dissolution of aragonite and creation of a void in which calcite is precipitated, or as an *in situ* process of

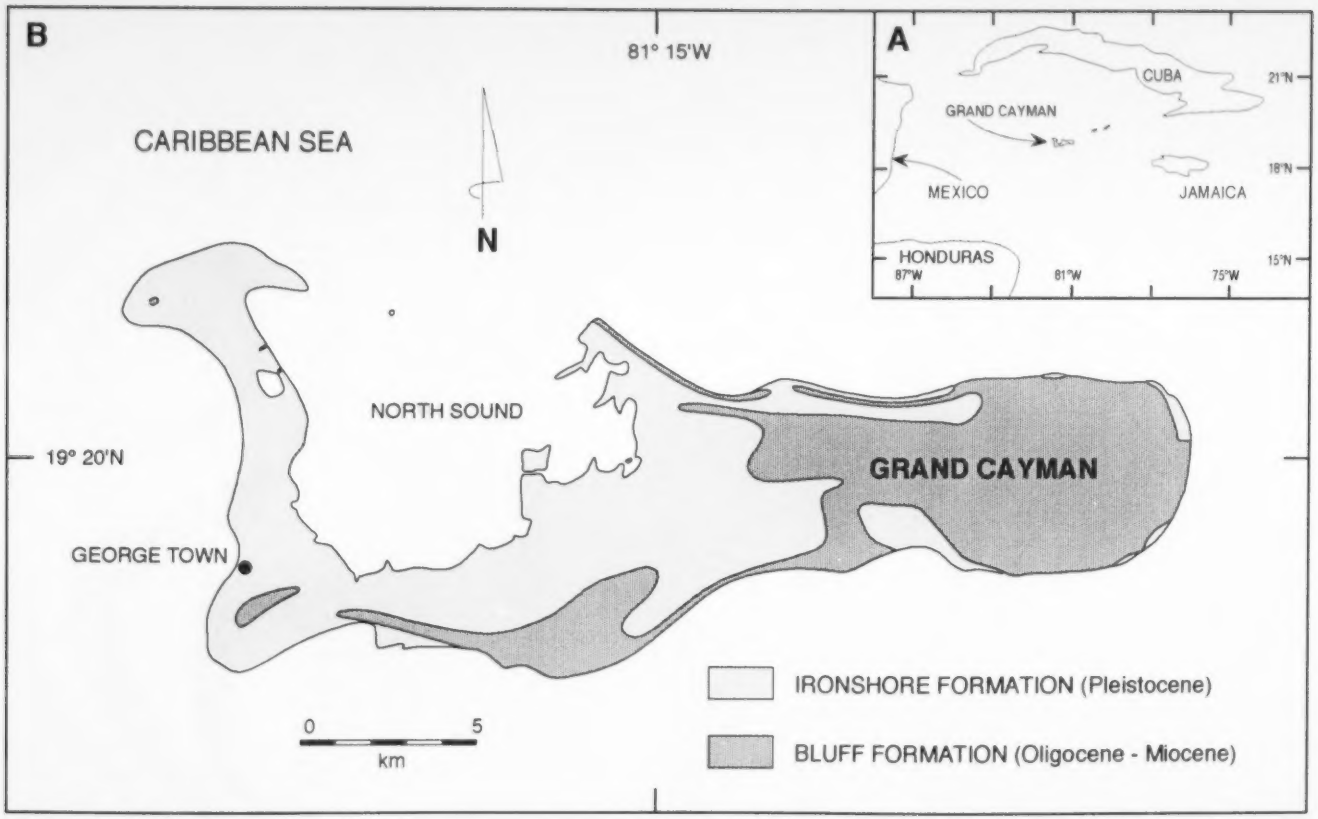


Figure I-1. A. Geographical location of Grand Cayman in the Caribbean. B. Geological map of Grand Cayman. Modified from Hunter and Jones (1989, Figure 1).

dissolution/reprecipitation that occurs on a microscale and involves no appreciable void stage.

In the Ironshore Formation, the process of replacement of aragonite by calcite is largely incomplete. This provides an opportunity to examine intermediate stages of aragonite to calcite alteration in skeletal components. By examining numerous samples displaying varying degrees of alteration, the full spectrum of changes leading up to complete mineralogical stabilization can be determined. This spectrum of textural evidence provides a basis for understanding the nature of aragonite to calcite diagenetic processes, and provides criteria for recognizing the processes responsible for various diagenetic products.

A. LATE PLEISTOCENE PALEOGEOGRAPHY AND SEDIMENTOLOGY

The Ironshore Formation was deposited during a +6 m sea level highstand in the late Pleistocene (Jones and Hunter 1990), 120,000 to 130,000 years ago (Woodroffe *et al.* 1983). These limestones were deposited in a large lagoon, named the Ironshore Lagoon by Hunter and Jones (1988), that covered the central and western parts of the island, and in small embayments along the south, east and north coasts (Figure I-2).

Hunter and Jones (1989) defined 13 facies, based on lithology and sedimentary structure (Table I-1), that were deposited in a wide range of environments including lagoon, patch reef, inter-reef, reef channels and reef tract (Figure I-3). In the interior of the lagoon, where quiet shallow water conditions prevailed, bivalve facies A and B were deposited. The western part of the lagoon was characterized by patch reefs up to 300 m in diameter (coral facies A), surrounded by inter-reef deposits (skeletal grainstone facies, moderately burrowed grainstone facies, and highly burrowed grainstone facies).

Erosion of the extensive barrier reef along the western edge of the island since the Late Pleistocene has removed the reef crest; however, the back-reef portion of the reef tract is preserved as a linear outcrop belt along the west, northwest and southwest coasts

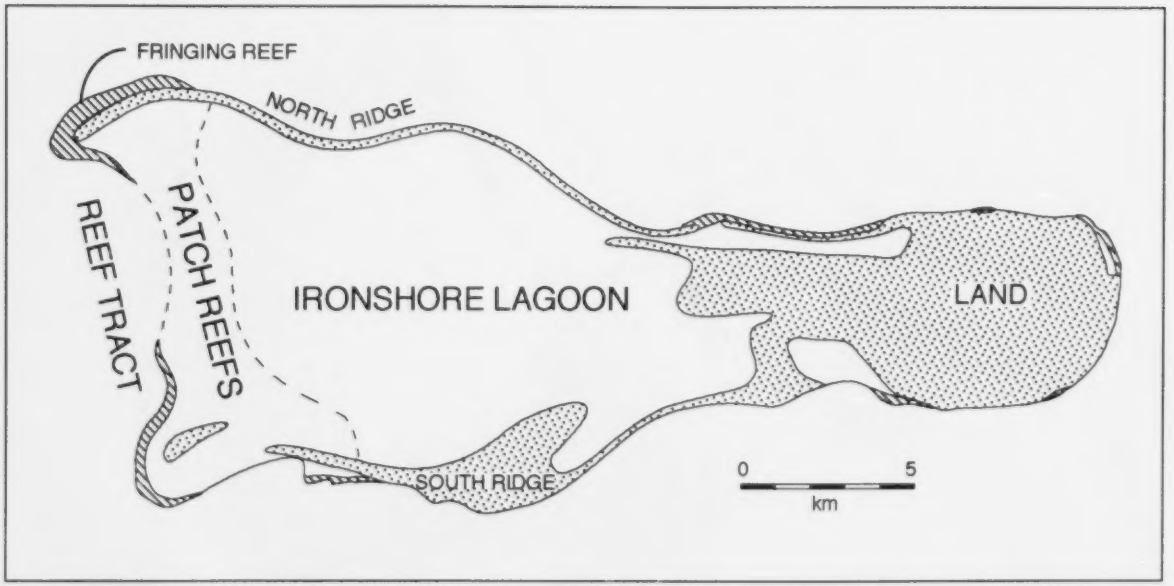


Figure I-2. Paleogeographic map of Grand Cayman 120,000 to 130,000 years ago. Modified from Hunter and Jones (1989, Figure 1).

FACIES	LOCALITIES	LITHOTYPE	SORTING	GRAIN SIZE	SEDIMENTARY STRUCTURES	FOSSILS		TRACE FOSSILS *	ENVIRONMENT
						DOMINANT	MINOR		
Bivalve A	MA, TSE	skeletal wackestone to packstone	poor	silt to very fine	N/O	bivalves	gastropods foraminifera	N/O	Lagoon
Bivalve B	EOR, DSB, NSE, OG, OGA, HSB, BWD, TG	skeletal packstone to grainstone	moderate to poor	very fine to fine	N/O	bivalves	corals *Halimeda* gastropods	N/O	Lagoon
Coral A	MOS, MH, A, B, C, D, E, F, G, I, J, K, CYA, CYB, PSI, VV, PBA, PBQ, WKR, SDA, SDB	coral floatstone	poor	fine to coarse	N/O	corals	bivalves gastropods	*Gastrochaenolites Entobia Trypanites*	Patch reefs
Skeletal Grainstone	H, MDA, MDC, MON, TS, CYC, U, CNP, GC, PWA, PWD, SD, SDC	skeletal grainstone	moderate	fine to coarse	moderate burrowing	none	corals bivalves	*Polykladichnus Skolithos*	Inter-reef
Coral B	GTP, LSP, SPB, CPA, TC, SB, SBJ, PL, IP, ML, PP, TJU, AB, SH, SHB, EOT, CDS, ER, AS, AC, ACG, DP, DPC, DPD, DPQ, WB, TF, BT, BTD, BTH	coral boundstone	poor	fine to coarse	N/O	corals	gastropods red algae	N/O	Reef tract
Well Sorted Skeletal Grainstone	SBB, SBD, ACH, ADF, ABB, ABC, TFB, MB	skeletal grainstone	well	fine to medium	N/O	none	corals	N/O	Reef Channel
Moderately Burrowed Grainstone	SC, L, M, N, PBQ, BQ	ooid grainstone	well	fine to medium	laminated moderate burrowing	none	none	*Ophiomorpha Polykladichnus Skolithos, Conichnus*	Subtidal
Highly Burrowed Grainstone	SC, LSC, BQ, PBA, PBQ, MHA	ooid grainstone	well	fine to medium	high burrowing	none	none	*Ophiomorpha Polykladichnus Skolithos, Planolites*	Subtidal
Unidirectional Cross-bedded Grainstone	SC	ooid grainstone	well	fine to medium	unidirectional high-angle cross-bedding low burrowing	none	none	*Polykladichnus Skolithos, Conichnus Bergaueria, Psilonichnus*	Subtidal
Multidirectional Cross-Bedded Grainstone	SC, LSC, PBQ, PBA, PMP, SB, SBA, SBE, SBF, SBG, ACA, ACH, WRS, BQ	ooid grainstone	well	fine to medium	multidirectional high-angle cross-bedding moderate burrowing	none	none	*Ophiomorpha Skolithos*	Upper shoreface
Lithoclast Rudstone	SC	lithoclast rudstone	moderate	fine to medium	high burrowing	none	none	*Ophiomorpha Polykladichnus Conichnus*	High energy subtidal
Bioclast Floatstone	SC	bioclast floatstone	moderate	fine to medium	high-angle cross-bedding moderate burrowing	none	corals bivalves	*Ophiomorpha Polykladichnus Skolithos*	High energy subtidal
Laminated Grainstone	LSC, PBQ, PBA, BQ, SBA	ooid grainstone	well	fine to medium	laminated to low-angle cross-bedding	none	none	none	Foreshore-backshore

Table I-1. Summary of lithology, fossils, and trace fossils for facies of the Ironshore Formation. N/O = not observed due to poor exposure. *Trace fossils in Coral A Facies from Jones and Pemberton (1988*a*, 1988*b*); all other trace fossils from Pemberton and Jones (1988) and Jones and Pemberton (1989). Modified from Hunter and Jones (1989, Table 1).

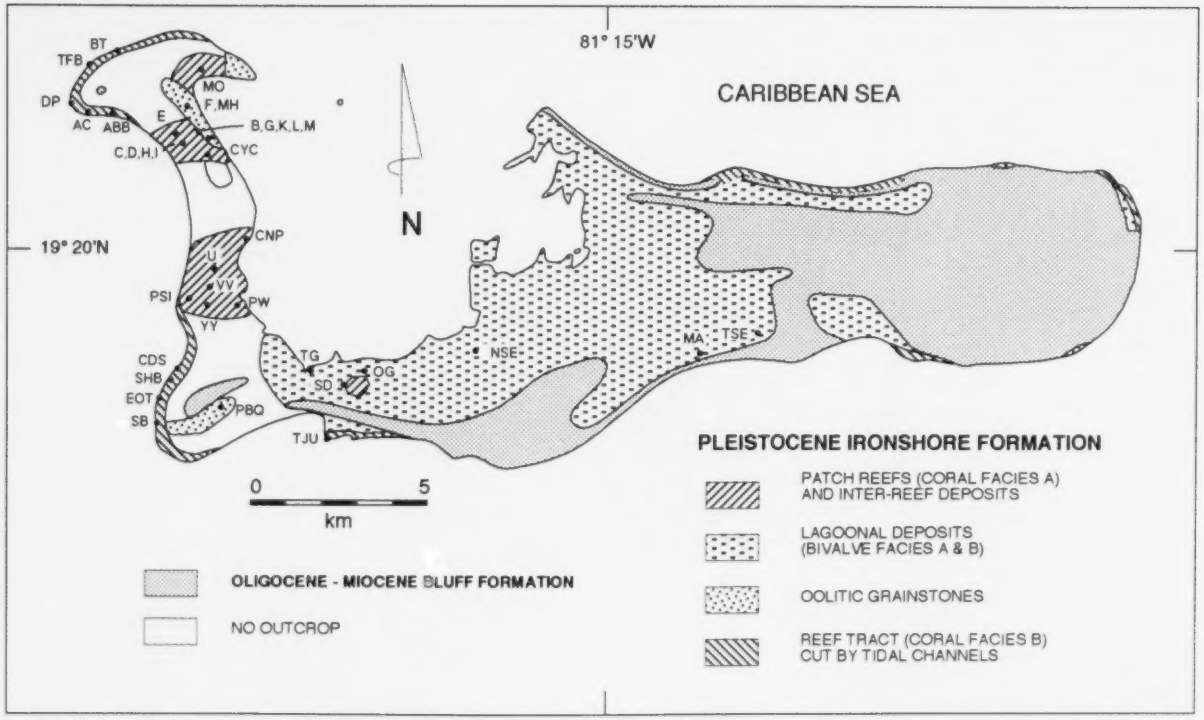


Figure I-3. Map of Grand Cayman showing positions of Pleistocene localities relative to depositional environment and facies. Modified from Hunter and Jones (1988, Figure 2). Localities are grouped on the map as follows: AC=ACB, ACF, ACG, ACH; BT=BTD, BTH; DP=DP, DPC, DPD, DPQ; MH=MH, MHA; MO=MOA, MON, MOS; OG=OG, OGA; PW= PWA, PWD; SB=SBB, SBD, SBE, SBG; SD= SD, SDA, SDB, SDC).

(Hunter and Jones 1989). It is characterized by a coral framestone to rudstone with a grainstone matrix (coral facies B), that is cut by a series of tidal channels (well sorted skeletal grainstone facies). The reef tract is represented by a diverse assemblage of corals, many of which are absent from the patch reefs (coral facies A) because they are incapable of sediment rejection (Hunter and Jones 1988).

B. OBJECTIVES

This thesis documents and explains the origin of diagenetic textures in Pleistocene gastropods and corals, based on detailed petrographic examination of thin sections, and scanning electron microscopy. The specific objectives are to:

1. provide descriptions of diagenetic textures in *Strombus gigas*, *Siderastrea siderea*, and *Montastrea annularis*,
2. develop a diagenetic model for aragonite to calcite alteration, and cementation, for each of these skeletal components,
3. compare the style and mode of diagenesis between these three taxa,
4. relate diagenetic textures to differences in skeletal structure and microstructure, and
5. discuss and develop criteria for differentiating neomorphic spar from cement.

C. METHODS

Seventy-six *Strombus gigas* (Table I-2), 32 *Siderastrea siderea* (Table I-3), and 137 *Montastrea annularis* (Table I-4) were collected from 55 localities (Figure I-3) in the Pleistocene Ironshore Formation of Grand Cayman (see Appendix A for UTM coordinates). These samples were obtained from surface exposures, and material removed from dike canals and excavations.

Detailed petrographic analysis involved examination of 22 thin sections of *Strombus gigas*, 10 thin sections of *Siderastrea siderea*, and 22 thin sections of *Montastrea annularis*. Four samples of *Strombus gigas*, four of *Siderastrea siderea*, and three of *Montastrea*

LOCALITY	NUMBER OF SPECIMENS	SAMPLE NUMBERS	THIN SECTIONS	SEM
ABB	1	2753	2753	
ACB	1	2729		
ACF	1	2737	2737	
ACG	1	2743		
B	3	1439, 1971, 1972		1439
BTD	1	2619		
BTH	1	3299		
C	5	1451, 1984, 1988, 1900, 1989	1990	1984
CDS	1	2836		
CNP	2	2119, 3346	3346	
CYC	2	2769, 2926	2926	
D	1	2057		
DPD	1	2700		
E	1	2063	2063	
EOT	1	2812	2812	
F	2	2070, 2079		
H	1	2094	2094	
K	2	1941, 2103, 2115		
L	1	2609		
M	1	2614	2614	
MA	1	2202	2202	
MHA	1	2589		
MOA	4	1893, 1894, 1954, 1960	1893	
MON	3	1891, 1949, 1950		
MOS	1	1963		1963
NSE	1	2201		
OG	2	2191, 2192,		
OGA	3	2195, 2196, 3482	2196	
PBQ	1	2892	2892	
PSI	2	1528, 1529	1528	
PWA	2	2141, 2145		
PWD	2	2148, 2149		
SBB	1	2796		
SBD	1	2800	2800	2800
SD	5	1845, 1846, 2164, 2165, 2166	1846	
SDA	1	2177	2177	
SDB	2	2181, 2183		
SDC	2	2856, 2857		
SHB	1	2823		
TFB	1	2648		
TG	3	2156, 2157, 2160	2160	
TSE	3	2207, 2209, 2965	2207, 2965	
U	1	2126	2126	
VV	1	2130	2130	
YY	1	2134	2134	
TOTALS	76		23	4

Table I-2. List of samples of *Strombus gigas* from the Pleistocene Ironshore Formation. See Figure I-3 for map localities.

LOCALITY	NUMBER OF SPECIMENS	SAMPLE NUMBERS	THIN SECTIONS	SEM
BTH	1	2641		
C	2	1462, 2048	1462, 2048	2048
CNP	2	1820, 2120		
CYC	6	2778, 2779, 3018, 3034, 3302 3303, 3305	2779A, 3302 3304	3302A 3302B
D	1	3007		
E	2	1781, 2065	2065	
F	3	1694, 1695, 2073		
G	1	1766, 2597		
MH	3	1516, 2574, 2576	2574	2574
MON	1	1788		
SDA	3	1851, 2179, 2180	1851, 2180	
SDB	3	1859, 2182, 2184	1859	
SDC	1	2860		
U	1	1799		
VV	3	1800, 1805, 2128		
TOTALS	32		10	4

Table I-3. List of samples of *Siderastrea siderea* from the Pleistocene Ironshore Formation. See Figure I-3 for map localities.

LOCALITY	NUMBER OF SPECIMENS	SAMPLE NUMBERS	THIN SECTIONS	SEM
ACB	2	2727, 2730	2727	
ACF	1	2739		
ACH	1	2749		
B	10	1436, 1437, 1438, 1445, 1785, 1975, 1977, 1979, 1980, 1982	1436, 1785	
BTD	5	2622, 2632, 2633, 2636, 2637	2632, 2636	
BTH	1	2644	2644	
C	18	1454, 1458, 1461, 1463, 1475, 1649, 1650, 1760, 1987, 1991, 1992, 1994, 1995, 1996, 2988, 3408, 3409, 3410	1987, 1992A, 1992B, 1996	1987
CDS	1	2838		
CNP	2	1819, 2121		
CYC	7	2768, 2776, 2779, 2782, 2785, 2915, 2917	2779B	2768
D	4	1736, 2053, 2055, 2059		
DP	9	1537, 1538, 1539, 1540, 2682, 2683, 2684, 2687, 2690		
DPC	1	2697	2697	
DPQ	2	2713, 2715		
E	2	1777, 2064		
EOT	1	2811	2811	
F	7	1698, 1700, 1701, 1718, 2076, 2078, 2761	2761	
G	8	1765, 2082, 2083, 2084, 2087, 2224, 2226, 2596		
H	3	1775, 2095, 2096	2096	
I	2	2600, 2602		
K	4	1688, 2114, 2607, 2608	2114	
MH	14	1501, 1503, 1506, 1510, 1511, 1512, 1517, 1518, 1520, 1522, 1523, 1524, 2577, 2587		
MON	1	1787		
MOS	5	1792, 1795, 1796, 1966, 1968	1795, 1968	
OGA	2	2669, 3481		
PSI	5	1526, 1527, 1530, 1531, 1535	1530	
SBE	1	2928		
SBG	1	2808		
SDA	2	2172, 2179		
SDB	3	1864, 2185, 2855	2855	
SHB	1	2820		
TFB	3	2655, 2665, 3300		
TG	2	2155, 2161	2155	
TJU	1	2832		
TSE	1	2966	2966	
VV	1	2131		
YY	3	1812, 1817, 2136		
TOTALS	137		22	2

Table I-4. List of samples of *Montastrea annularis* from the Pleistocene Ironshore Formation. See Figure I-3 for map localities.

annularis were polished, etched with 5% HCl and examined on the scanning electron microscope.

Complete or near-complete shells of *Strombus gigas* were serially sectioned and stained with Feigl's solution (Feigl 1937, p. 328-329: see Appendix B for detailed methodology). This allowed the calcite/aragonite distribution in the shell to be mapped in three dimensions. Proportions of aragonite and calcite, and the percentage of shell removed by the boring action of sponges, were determined by point counts of photographic prints of thin sections using an average of 670 points (range: 300 to 1200). These values are accurate to within 2 to 5% at a confidence level of 95%. This error margin is based on estimates of probable error provided by Galehouse (1971, Figure 5, p. 398).

D. OCCURRENCE OF *STROMBUS GIGAS*, *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS*

Modern *Strombus gigas* lives in the intertidal and shallow subtidal zones down to a depth of at least 36 m (Javidpour 1978). They are found primarily in beds of *Thalassia testudinum* and *Syringodium filiforme*, or on sand flats, but are also present to a lesser extent on gravel, coral rubble and reef, when not too irregular or steep (Randall 1964). *Strombus gigas* is a herbivorous organism which feeds mainly on epilithic algae on sea grass (Randall 1964).

On Grand Cayman during the Pleistocene, *Strombus gigas* was most common in lagoonal and inter-reef environments (Figure I-4). *Strombus gigas* was not present on patch reefs and the reef tract, but was abundant in areas between patch reefs and common in channels through the reef tract. Although *Strombus gigas* has been collected from patch reef localities (Table I-2), it is not a component of coral facies A, but rather forms part of inter-reef deposits that are proximal to patch reefs. Based on molluscan associations, Cerridwen (1989) established that mixing between inter-reef and patch reef deposits was considerable, due to mixing of sediments during excavations and collection of samples over

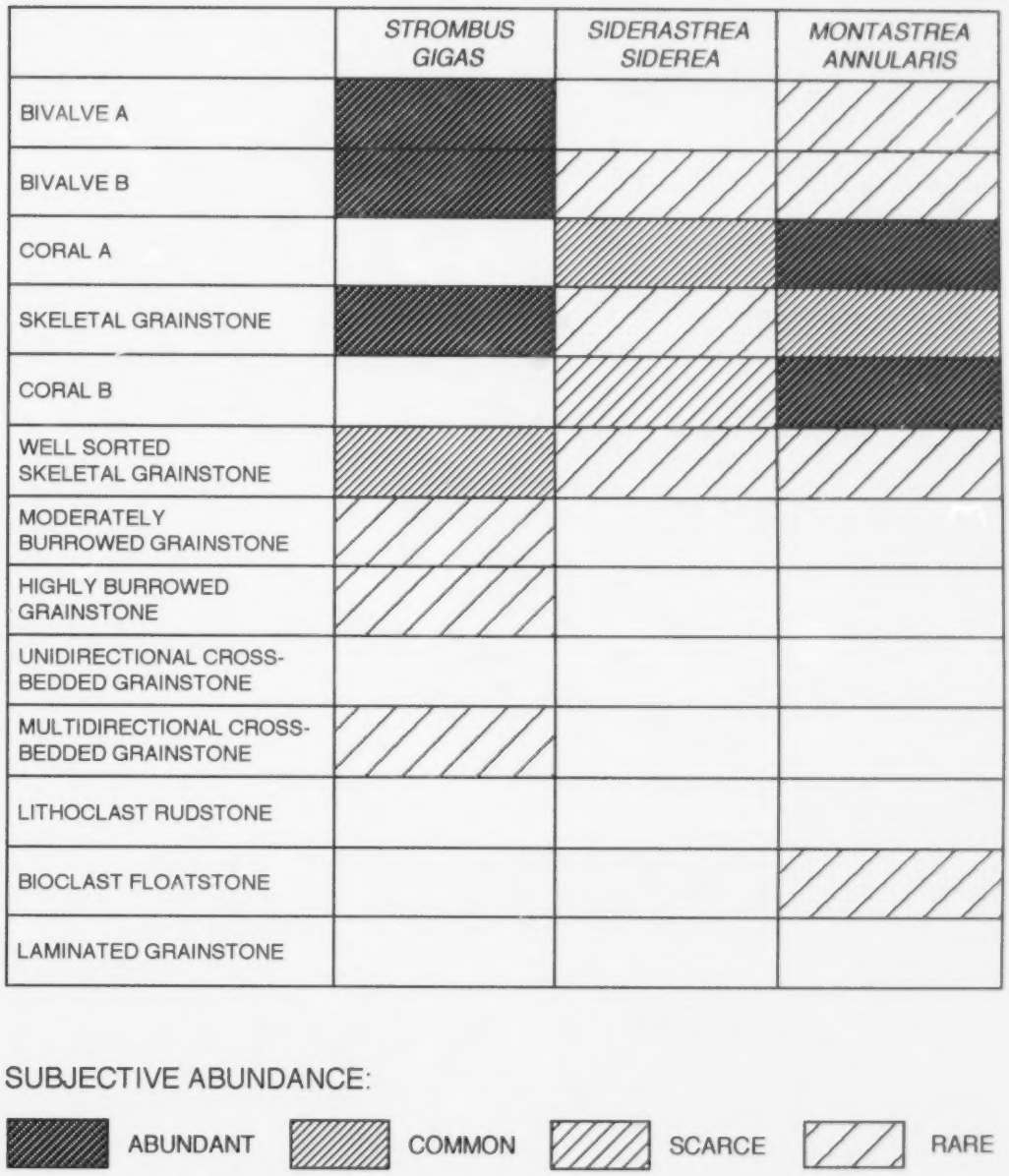


Figure I-4. Distribution of *Strombus gigas*, *Siderastrea siderea*, and *Montastrea annularis* in facies of the Ironshore Formation. Abundance data for *S. siderea* and *M. annularis* from Hunter and Jones (1988) and Hunter (1990 pers. comm.).

areas containing both facies. Samples of *Strombus gigas* from patch reef localities are therefore treated as part of the inter-reef limestones.

Scleractinian corals such as *Montastrea annularis* and *Siderastrea siderea* live in normal salinity waters and generally colonize a hard substrate (Wells 1956). They are abundant in modern lagoons and on reefs surrounding Grand Cayman. The bathymetric ranges for *Siderastrea siderea* and *Montastrea annularis* are 0.5 to 70 m, and 0.3 to 80 m, respectively (Goreau and Wells 1967).

Montastrea annularis and *Siderastrea siderea* were chosen for study because they are common and have a wide distribution with respect to sedimentological facies (Hunter and Jones 1988, 1989). These corals are capable of sediment rejection, and live in a wide variety of environments (Hubbard and Pocock 1972). This wide distribution contrasts with that of other corals such as *Acropora palmata* and *Acropora cervicornis* that are confined to the reef tract because they are incapable of sediment rejection.

In the Ironshore Formation, *Siderastrea siderea* and *Montastrea annularis* are most common in the patch reefs and the reef tract, but also occur as isolated colonies in lagoonal and inter-reef areas (Figure I-4). *Siderastrea siderea* is less abundant and has a more restricted distribution than *Montastrea annularis* (Figure I-4).

E. TERMINOLOGY

Following James and Choquette (1983), the term **cement** herein refers to any pore-lining or pore-filling carbonate precipitate, regardless of whether it acts as a binding agent or simply fills internal pores. This usage agrees with that of Bathurst (1975, p. 416), who applied the term to "...all passively precipitated, space-filling carbonate crystals which grow attached to a free surface...". Cements are precipitated in original cavities (e.g. intraskeletal pores of corals, on and between skeletal components and grains) or in voids created by dissolution or bioerosion.

In situ transformations between a mineral and itself or a polymorph in the absence of an appreciable void stage are what Folk (1965) referred to as **neomorphism**. This broad term includes the process of **recrystallization** - which involves no change in mineralogy, but only changes in crystal size, shape or orientation; and **inversion** - which refers to neomorphic transitions between a mineral and its polymorph. The process of inversion has also been referred to as ***in situ* recrystallization** (Bathurst 1964, p. 371), **paramorphic replacement** (Friedman 1964), and **polymorphic replacement** (Bathurst 1975, p. 476). In its strictest sense, the term **replacement** was used by Folk (1965) for changes between one mineral and another of a different composition, though he recognized that it is widely used to refer to any mineralogic transformation, including inversion.

Inversion is an *in situ* process, and as such it commonly results in the preservation of primary microstructure and/or relics of the original polymorph. By contrast, a cement that is precipitated in a void created by dissolution of an earlier phase may preserve the external form of the cavity, but does not retain evidence of the original internal structure. The dominant product of aragonite to calcite inversion in the meteoric realm is a calcite spar, which due to its neomorphic origin, may be referred to as **neomorphic spar**. This usage is consistent with that of Bathurst (1975) and Schneidermann *et al.* (1972), and is convenient in distinguishing this type of spar from calcite cement.

The term **micrite** was originally introduced by Folk (1959) to refer to clay-sized matrix which characterizes low energy deposits. Since its initial application, it has been used in a variety of ways, both as a purely descriptive term and as a descriptive term with genetic connotations. Friedman and Sanders (1978) and Friedman (1985*a*, 1985*b*) argued that because matrix typically refers to mechanically deposited material between particles, the term **micrite** should be restricted to "... lithified mechanically deposited lime mud...". Furthermore, Friedman (1985*b*) argued that the term **micrite cement**, as used by Alexandersson (1969), Ginsburg *et al.* (1971), James *et al.* (1976), James and Ginsburg

(1979), Land and Moore (1980), Marshall and Davies (1981), Marshall (1983), Hook *et al.* (1984), and Coniglio *et al.* (1988) is a contradiction of terms. Despite this, Milliman *et al.* (1985), Macintyre and Marshall (1988), and Jones (1989) have recognized the need for a term which can be used for descriptive purposes that does not carry genetic implications. Such usage is imperative due to the difficulty in establishing criteria to distinguish finely crystalline calcite cement from clay-sized sediment. The term micrite is therefore used herein to refer to grains or crystals less that 4 μm in size, regardless of their origin.

McKee and Gutschick (1969) applied the term **peloid** to allochems formed of microcrystalline or cryptocrystalline material, irrespective of their size or origin. Bathurst (1975) noted that the term is useful because it allows reference to grains of microspar or micrite without the need to imply any particular mode of formation. The term peloid therefore encompasses a wide variety of particles including fecal pellets, micritized skeletal particles and other altered grains, calcified bacterial clumps (Chafetz 1986) and inorganic cement precipitates (Macintyre 1985).

E. TEXTURAL CRITERIA FOR THE RECOGNITION OF CEMENT AND NEOMORPHIC SPAR

The differentiation of neomorphic spar and cement in thin section requires a knowledge of certain fabric criteria (Table I-5). This task can be difficult because neomorphic spar may exhibit textural characteristics that are the same as cement. For example, although crystal size in neomorphic spar commonly varies irregularly from place to place (Bathurst 1975), it may also show a regular vectorial increase in crystal size. Despite these problems, several textures are indigenous to neomorphic products, and thus can be used as textural criteria for identification purposes. The most reliable criteria for identifying neomorphic spar is the presence of relict structures and inclusions, because these cannot be preserved by complete dissolution and subsequent precipitation of cement.

CEMENT	NEOMORPHIC SPAR
Margin of sparry mosaic coincides with surfaces that were once free, such as surfaces of skeletal particles or ooids or molds of aragonitic shell fragments	Skeletal structures, depositional structures and particles transected by sparry calcite
Contacts between spar and particles sharp	Neomorphic spar transects older fabrics such that crystals at margins of neomorphic mosaic embay crystals of material being replaced
Spar lines cavity which it fills incompletely, or occupies the upper part of cavity whose lower part is occupied by a more or less flat-topped (geopetal) sediment	Spar is not associated with discernible voids or cavities
Spar is interstitial (interparticle) with well-sorted and abraded particles in depositional contact with each other	Floating relics of original material (patches of micrite, peloids, skeletal remnants) completely surrounded by spar.
Relic structures absent	Linear arrangements of relic inclusions cut across calcite mosaic, continuing without deviation across intercrystalline boundaries
Crystal size increases away from initial substrate; commonly two or more generations of spar	Crystal size commonly varies irregularly from place to place but may also show a regular vectorial increase in crystal size
Crystals of mosaic have preferred orientation of long axes and optic axes normal to initial substrate	Crystal orientation may be either random, or exhibit a radial-fibrous arrangement
Intercrystalline boundaries planar	Intercrystalline boundaries vary from curved to wavy
High percentage of enfacial junctions (triple junctions with one angle equal to 180°)	Enfacial junctions rare
Crystals typically clear with straight extinction	Crystals may be pale brown and pleochroic, with undulose extinction

Table I-5. Textural criteria for the recognition of cement and neomorphic spar. Modified from Bathurst (1975).

II. SKELETAL MORPHOLOGY AND STRUCTURE OF *STROMBUS GIGAS, MONTASTREA ANNULARIS* AND *SIDERASTREA SIDEREA*

Critical to the understanding of aragonite to calcite alteration in Ironshore skeletal components is a detailed knowledge of original skeletal morphology and structure. The purpose of this chapter is to provide a review of morphological features and microstructural elements of *Strombus gigas*, *Siderastrea siderea*, and *Montastrea annularis*, and to establish a framework for recognition of altered portions of the skeleton and description of diagenetic textures.

A. *STROMBUS GIGAS*

Shell Morphology

Strombus gigas is a dextrally spiraled (coiled from left to right as seen from the apex), evolute gastropod with well developed spines on the spire almost to the apex (Plate II-1A). In its adult form, the aragonitic shell is 15 to 30 cm long, has a flaring outer lip and small U-shaped indentation or stromboid notch at the base of an elongated aperture. Shell thickness ranges from 2 mm in the inner whorls, to more that 2 cm in the columella and lip.

Strombus gigas, commonly known as the 'queen conch' or 'pink conch', is readily distinguished from other Strombids by its large adult size, widely expanded lip, and in modern species, its pink, yellow and orange coloration in the aperture (Clench and Abbott 1941; Abbott 1974).

Damage to the shell by boring and movement over sand and rock substrate is periodically repaired by deposition of new skeletal material along the inner edge of the shell. The spines and apex of the spire cannot be protected by new layers; thus, they become bluntly rounded and gradually diminish in size (Randall 1964).

Plate II-1

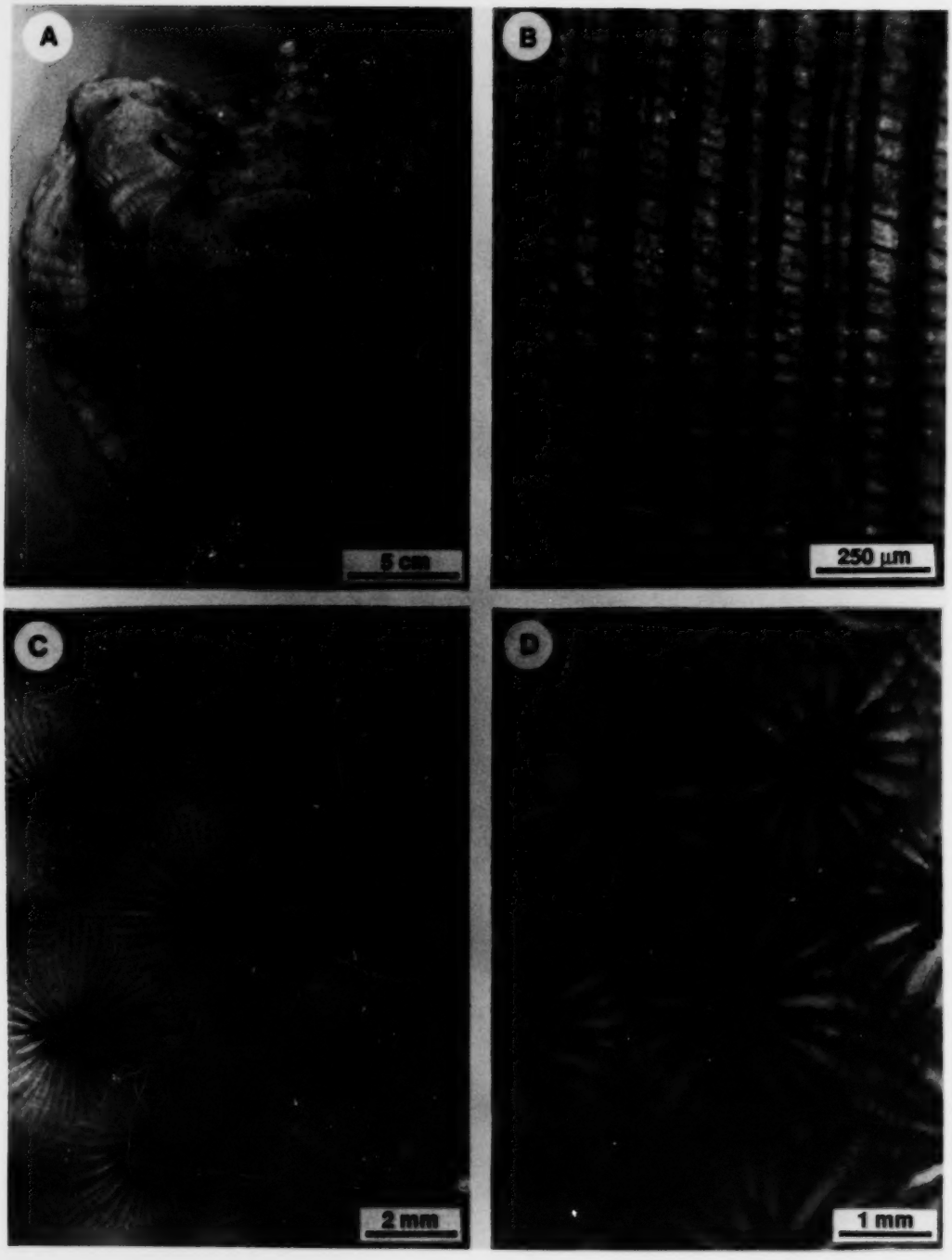
Skeletal structure and microstructure of *Strombus gigas*, *Siderastrea siderea* and *Montastrea annularis*.

(A) Photograph of the shell of *Strombus gigas* (#2648, CR #285, Loc. TFB).

(B) Thin section photomicrograph of crossed-lamellar structure in *Strombus gigas*. First order lamellae are oriented N-S, and second order lamellae are WNW-ESE and WSW-ENE (#2892, Loc. PBQ).

(C) Photograph of *Siderastrea siderea*. Colonies are cerioid. Corallite walls are defined by fenestrate synapticulothecae (Modern sample provided by I. Hunter).

(D) Photograph of *Montastrea annularis*. Colonies are plocoid. Corallite walls are separated by coenosteal elements including costae and exothecal dissepiments (Modern sample provided by I. Hunter).


A
5 cm
B
250 µm
C
2 mm
D
1 mm

Skeletal Microstructure

The shell of *Strombus gigas* is formed of four layers of aragonite with alternating orientations of crossed-lamellar structure. Crossed-lamellar structure (Plate II-1B; Figure II-1) is common to many groups of molluscs, and has been described in detail by Bøggild (1930), Taylor *et al.* (1969), Bathurst (1975), and Nakahara *et al.* (1981). Crossed-lamellar structure is always aragonite; however, the scale of structural components varies greatly between taxa.

In *Strombus gigas*, first order lamellae are rectangular plates 15 to 50 μm wide, that lie normal to the shell surface in the first and third layers of the shell, and oblique or longitudinal in the second and innermost layers. Each first order lamellae is formed of second order lamellae that lie perpendicular to the first order lamellae. Second order lamellae are 1 to 1.5 μm wide, and have opposed directions of inclination in adjacent first order lamellae (Figure II-1). The first order lamellae is a single entity with perfect uniform extinction, despite the fact that it is composed of a series of second order lamellae.

Second order lamellae are formed of numerous rod-shaped aragonite crystals assembled parallel to one another, and parallel to the tabular surface of the second order lamellae. These crystals are the basic microstructural unit of crossed-lamellar structure. They are 0.1 to 0.2 μm wide, 0.5 to 8 μm long (average 3 μm), taper slightly towards their ends, and have rounded terminations.

B. *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS*

Skeletal Morphology

Siderastrea siderea

In the Ironshore Formation, *Siderastrea siderea* occurs as massive, hemispherical colonies up to 2 m in diameter. This coral is characterized by cerioid colonies with closely spaced cups or calices that share a common wall (Plate II-1C). Individual calices are 4 to 5

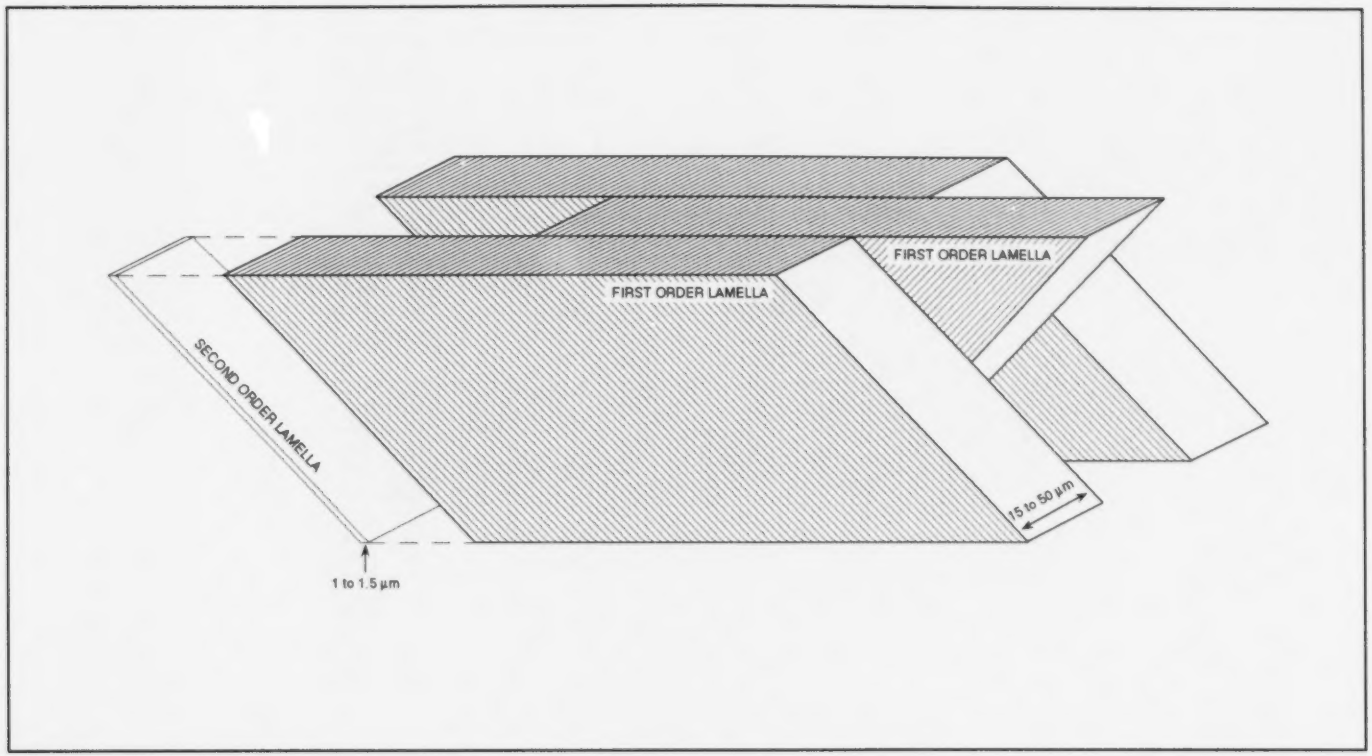


Figure II-1. Schematic diagram of crossed-lamellar structure. The orientation of first order lamellae relative to the shell surface is variable depending on location in the shell. Modified from Bøggild (1930).

mm in diameter, and up to 3 mm deep (Vaughan 1919). There are typically more than 48 septa, in five septal cycles; the fifth being incomplete. The columella is small and papillary. The inner edges of the septa slope gently (45°) towards the columella, resulting in a wide fossa.

Adjacent septa are connected by 3 to 4 rows of synapticulae which perforate the mesenteries between adjacent septa. Between each adjacent pair of septa there are 3 to 4 rows of synapticulae. Well defined corallite walls (thecae) are formed of several synapticular rings (Wells 1956).

In addition to synapticulae, there are horizontal dissepiments between septa which support the polyp and separate it from lower parts of the skeleton (Duerden 1904). In *Siderastrea siderea*, these are endothecal dissepiments because corallites share a common wall and all dissepiments occur in a calice.

Montastrea annularis

In the Ironshore Formation, the dominant growth forms of *Montastrea annularis* include massive hemispherical and cauliflower-like colonies. These colonies are up to 2 m in height or diameter.

Montastrea annularis forms plocoid colonies, in which corallites have separated walls that are united by costae and dissepiments (Plate II-1D). Calices are circular or slightly deformed, 2 to 4 mm wide, and 0.5 to 2.0 mm apart (Vaughan 1919). There are 24 septa per calice, 12 of which reach the columella (Vaughan 1919). The margins of the first two cycles of septa are raised so that they are higher than the theca (exsert). The septa correspond to an equal number of costae, which extend across the calicular margin and join the septa of adjacent calices.

Both endothecal and exothecal dissepiments are present in *Montastrea annularis*. Endothecal dissepiments are thin, flat, and nearly horizontal, whereas exothecal dissepiments are curved (Vaughan 1919).

Skeletal Microstructure

The fundamental skeletal elements of scleractinian corals such as *Siderastrea siderea* and *Montastrea annularis* are minute aragonite fibres which occur in two distinct arrangements. Spherulitic clusters of aragonite needles, known as **sclerodermites** (Figure II-2A), account for almost all of the coral mass (Barnes 1970). Sclerodermites unite to form **trabeculae** (Figure II-2B), which are the building blocks of septa, synapticulae, costae and the columella (Duerden 1904; Vaughan and Wells 1943; Wells 1956; Bathurst 1975). A less common arrangement is that of aragonite fibres assembled in dense, fibrous **laminar sheets** with long axes of the needles transverse to the sides of the sheet (Wells 1956; Bathurst 1975). This type of arrangement is typical of the basal plate, dissepiments, and stereome.

Septa, synapticulae, costae and the columella are composed of sclerodermites 100 to 200 μm in diameter (Figure II-2A). The centers of sclerodermites are **centers of calcification** from which the long axes of aragonite fibres radiate in three dimensions (Bryan and Hill 1941; Wells 1956; Wainwright 1964; Bathurst 1975). Wainwright (1964) demonstrated that each aragonite fibre is formed of an aggregate of acicular aragonite crystals with "...c axes having a preferred orientation within 10° of the axis of the fibre, and with a and b axes randomly arranged" (Bathurst 1975, p. 26). In *Siderastrea siderea* sclerodermites are composed of aragonite crystals, 1 to 2 μm wide and up to 100 μm long, arranged in bundles 10 to 20 μm wide. The ends of these bundles are evident along the margins of septal pores.

Individual sclerodermites are united in linear series, to form pillars with circular cross sections equal to the diameter of the sclerodermites (Figure II-2B). These pillars are known as **trabeculae**, and contain continuous lines of closely spaced centers of calcification along their centers. Trabeculae are simple, if composed of a series of single sclerodermites, or compound, if composed of bundles of sclerodermites.

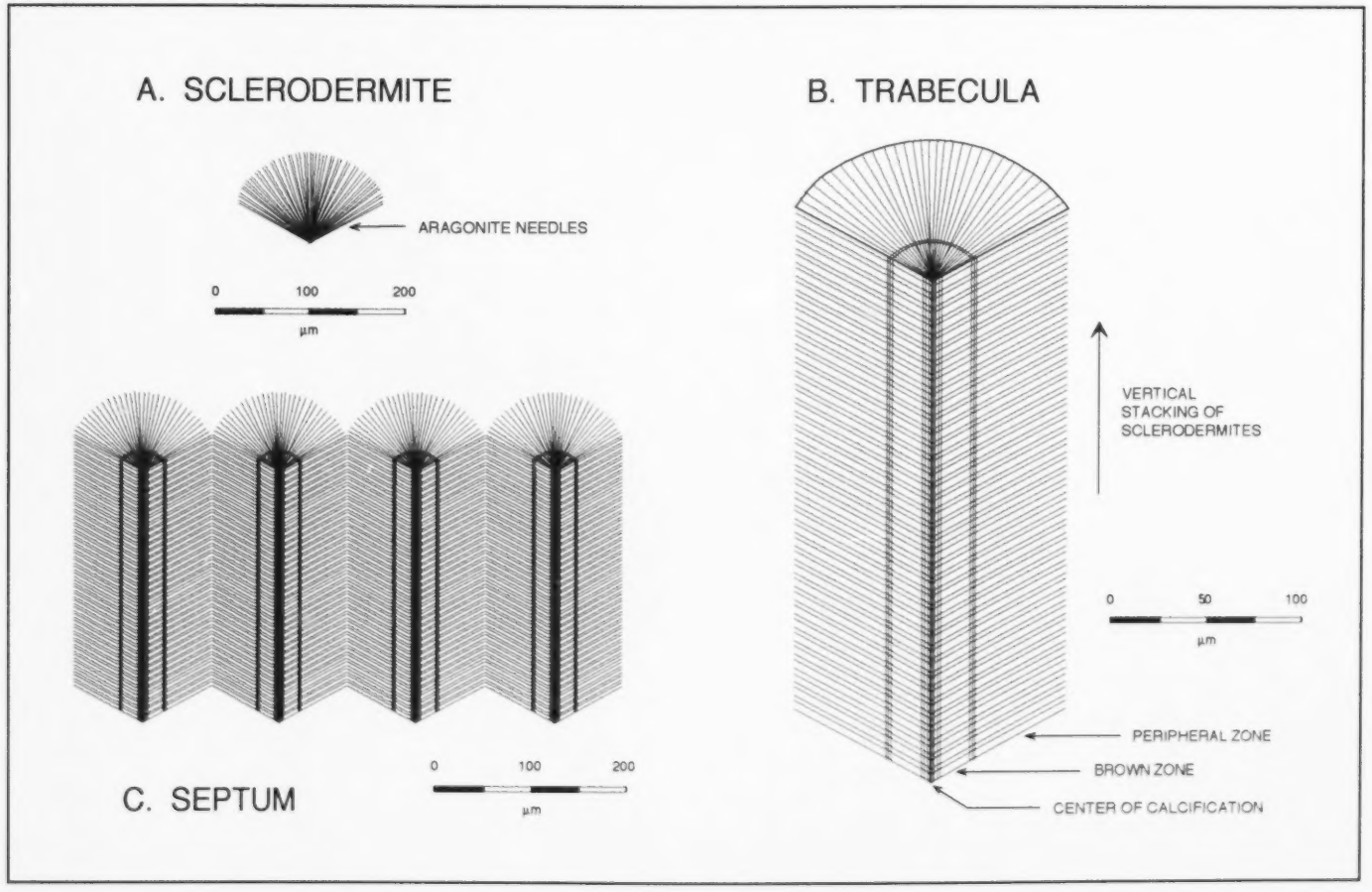


Figure II-2. Schematic diagram of basic scleractinian microstructure: A. Sclerodermite. B. Trabecula. C. Septum. Modified from James (1974).

Wainwright (1963, 1964) divided the trabecula into three zones, based on different crystal texture (Figure II-2B). The **Center of Calcification** consists of randomly oriented, small (less than 1 μm across), equant crystals of aragonite that appear dark brown to opaque in thin section because soluble organics fill intercrystalline pores. The **Brown Zone** consists of a combination of randomly oriented, equant crystals and oriented aragonite needles; pore spaces in this zone are empty. The **Peripheral Zone** of the trabecula consists of oriented, tightly packed aragonite needles with virtually no intercrystalline porosity.

Septa (Figure II-2C) represent palisades or fans of trabeculae, in which the trabeculae are inclined outwards from an axis of divergence (Wells 1956). Depending on how tightly or openly the trabeculae are packed, the septum may be laminar (closely spaced centers of calcification) or fenestrate (loosely connected trabeculae). Dentate septal margins result from septal granulations that occur where diverging centers of calcification emerge at the surface of a septum. **Synapticulae** are composed of trabeculae, and may have either a separate center of calcification, or be formed from extensions of the trabeculae in adjacent septa that join midway (Duerden 1904).

Trabecular structure is the dominant morphology of coral microstructure; however, some skeletal elements have a distinctly different morphology. The skeletal material of the basal plate, dissepiments and stereome (dense secondary skeletal deposit) consists of dense, fibrous sheets in which the long axes of the fibres lie normal to the surface of the sheet. These laminar sheets have no distinct centers of calcification, and are marked only by growth laminations (Wells 1956).

Bryan and Hill (1941) and Wainwright (1963) noted that there does not appear to be any difference between the fibres that form sclerodermites, and those which have a laminar arrangement. Rather, the orientation of the fibres is controlled by "...their invariable growth normal to the skeletogenic epithelium" (Bathurst 1975, p. 26). Trabecular fabric results from calcification in a sharply folded epithelium, whereas parallel fibres are

produced in the flat epithelium which controls the growth of the basal plate, dissepiments and stereome (Wells 1956; Wainwright 1963; Bathurst 1975).

Siderastrea siderea

The septa of *Siderastrea siderea* are composed of one fan system of small, predominantly simple trabeculae (Wells 1956). Trabeculae are widely spaced, with centers of calcification 125 to 200 μm apart; thus the septa are porous, with pores or perforations more or less regularly spaced between adjacent trabeculae. The upper margins of the septa are lined with septal teeth or dentations and the sides are strongly granulated (Wells 1956). The columella is composed of one or more papillary trabeculae (Wells 1956).

Between adjacent septa are synapticular rods formed by the union of trabeculae from two opposed septal granulations. The corallite wall or theca of *Siderastrea siderea* is also formed of synapticulae, thus it is referred to as a **synapticulotheca** (Wells 1956). The wall is fenestrate with regular perforations, and is shared by adjacent corallites.

Endothecal dissepiments represent transverse partitions which serve to cut off the living polyps from the dead part of the skeleton below (Duerden 1904). Unlike septa, dissepiments contain no centers of calcification, but they consist of thin (10 to 50 μm) laminar sheets in which aragonite fibres stand at right angles to the surface. Dissepiments occur at intervals of 0.6 to 0.8 mm along the length of the corallite.

Montastrea annularis

The septa of *Montastrea annularis* are formed of one fan system of mostly simple trabeculae (Wells 1956). The margins of both septa and costae are regularly dentate, and have granular sides (Vaughan 1919).

Both endothecal and exothecal dissepiments in *Montastrea annularis* are formed of dense sheets of aragonite crystals arranged at right angles to the margins of the sheet. The corallite wall is defined by layers of secondary thickening of the outer parts of the septa.

The secondary skeletal material, which forms the wall, is referred to as stereome, and has a non-trabecular structure similar to that of the dissepiments.

Montastrea annularis is characterized by a well developed trabecular columella, whose upper surface lies about 1 mm below the thecal margin (Vaughan 1919; Wells 1956). The diameter of the columella varies from about one third to one half the diameter of the calice.

III. DIAGENETIC ALTERATION OF *STROMBUS GIGAS*

Aragonitic shells of *Strombus gigas* have been altered by:

1. boring of the shell by bioeroders, particularly sponges,
2. partial or complete filling of these borings by internal sediments and cements, and
3. partial or complete alteration of the aragonitic shell to calcite. Shells of *Strombus gigas* are also commonly encrusted by bivalves, foraminifera and *Siderastrea siderea*.

A. SPONGE BORINGS

Pleistocene shells of *Strombus gigas* from Grand Cayman have been substantially altered by boring organisms. *Entobia* spp., produced by clionid sponges and to a lesser extent spirastrellid sponges (Bromley 1970; Bromley and d'Alessandro 1984; Pleydell and Jones 1988), are dominant. Boring has removed an average of 11% of the shell by volume, to a maximum of 38% (Table III-1).

Morphology and Distribution

Entobia spp. are characterized by a complex network of interconnecting, slightly irregular and/or elongate, spherical to ovoid chambers, 0.5 to 5 mm wide (Plate III-1A), that have pitted or scalloped walls (Plate III-1B).

Sponge borings are typically most dense along the outer edge of the lip of the shell, but also occur in the exposed portions of the spire and its spines (Figure III-1). The depth of penetration of sponge borings is typically less than 1 cm from the outer surface of the shell. The shell lip of adult *Strombus gigas* ranges in thickness from 2 to 2.5 cm, thus up to one-half of the lip has been altered by bioeroders.

SAMPLE	LOCALITY	FACIES	ENVIRONMENT	% BORING	% ARAGONITE	% CALCITE
1528	PSI	Coral A	Patch Reef / Inter-reef	1	60	40
1846	SD	Skeletal Grainstone	Inter-reef	23	75	25
1893	MOA	Skeletal Grainstone	Inter-reef	10	69	31
1990	C	Coral A	Patch Reef / Inter-reef	2	48	52
2063	E	Coral A	Patch Reef / Inter-reef	6	40	60
2094	H	Skeletal Grainstone	Inter-reef	23	26	74
2126	U	Skeletal Grainstone	Inter-reef	3	76	24
2130	VV	Coral A	Patch Reef / Inter-reef	9	36	64
2134	YY	Coral A	Patch Reef / Inter-reef	8	54	46
2160	TG	Bivalve B	Lagoon	2	60	40
2177	SDA	Coral A	Patch Reef / Inter-reef	28	89	11
2196	OGA	Bivalve B	Lagoon	38	13	87
2202	MA	Bivalve A	Lagoon	15	98	2
2207A	TSE	Bivalve A	Lagoon	0	100	0
2614	M	Moderately Burrowed Grainstone	Inter-reef	20	55	45
2737	ACF	Well Sorted Skeletal Grainstone	Reef Channel	8	47	53
2753	ABB	Well Sorted Skeletal Grainstone	Reef Channel	2	37	63
2800	SBD	Well Sorted Skeletal Grainstone	Reef Channel	1	29	71
2812	EOT	Coral B	Reef Tract	1	56	44
2892	PBQ	Moderately Burrowed Grainstone	Inter-reef	11	98	2
2926	CYC	Skeletal Grainstone	Inter-reef	8	53	47
3346B	CNP	Skeletal Grainstone	Inter-reef	30	0	100
			AVERAGES	11	55	45

Table III-1. List of thin sections of *Strombus gigas*. Facies and environments are from Hunter and Jones (1989). Percentage boring corresponds to the proportion of shell removed through excavation by bioeroders. Percentages of aragonite and calcite represent their relative proportions of the total area of shell that remains after boring. Values are based on point counts of photographic prints using an average of 670 points, and are accurate to within 2 to 5% at a confidence interval of 95%.

Plate III-1

Sponge borings, internal sediments and cements in *Strombus gigas*.

(A) Thin section photomicrograph of a spine of *Strombus gigas* that has been extensively bored by sponges. This interconnected network of irregular and/or elongate, spherical to ovoid chambers is typical of *Entobia* spp. (#2202, Loc. MA).

(B) Detailed view of an individual sponge boring in an aragonitic shell. Note the scalloped surface of the walls of the boring (#2892, Loc. PBQ).

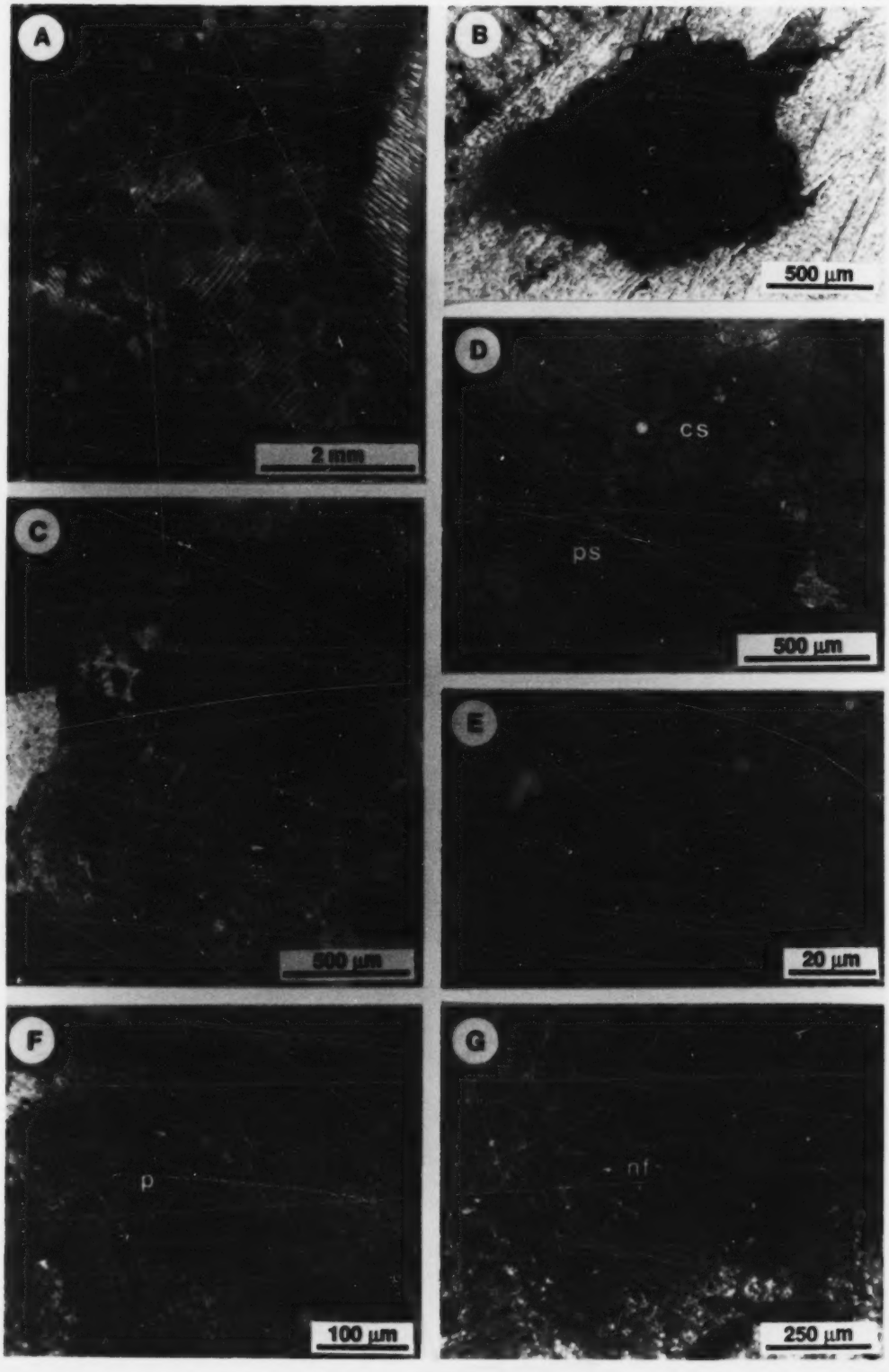
(C) Thin section photomicrograph of a sponge boring containing bivalve and coral fragments, and peloids. The allochems are encased by a dense layer of fluorescent micrite and cemented by pelsparite and blocky calcite spar (#1983, Loc. MOA).

(D) Thin section photomicrograph of a sponge boring containing pelsparite (ps) overlain by blocky calcite spar (cs) cement (#1528, Loc. PSI).

(E) SEM photomicrograph of growth zones in blocky calcite spar (#2800, Loc. SBD).

(F) Detailed view of pelsparite. Dense spherical to subspherical peloids (p) are surrounded by equant crystals of microspar (#1528, Loc. PSI).

(G) Thin section photomicrograph of a sponge boring containing a fibrous mat of randomly oriented needle fibre calcite (nf) crystals (#2965, Loc. TSE).


A
2 mm
B
500 µm
C
500 µm
D
cs
ps
500 µm
E
20 µm
F
p
100 µm
G
nf
250 µm

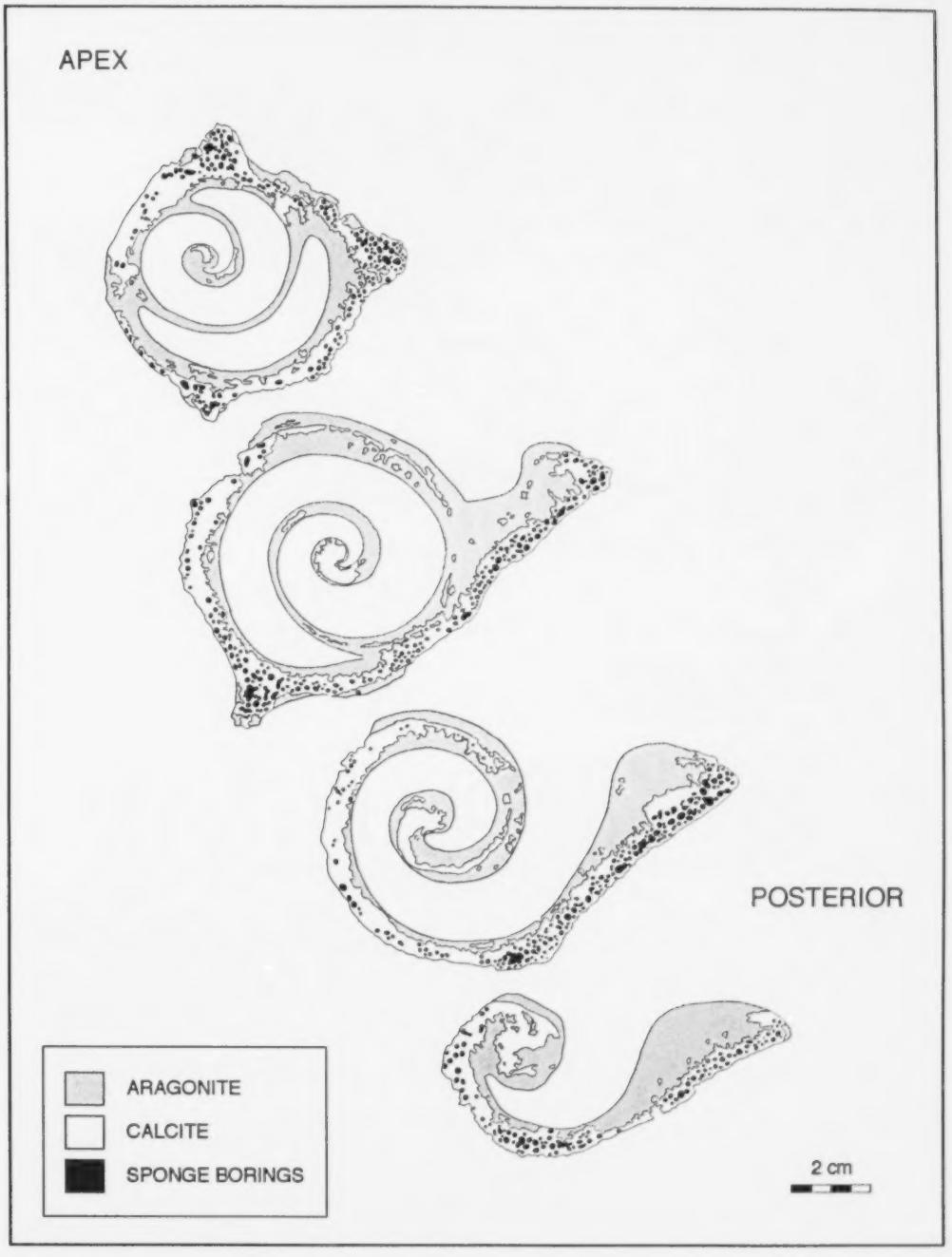


Figure III-1. Tracings of serial sections of *Strombus gigas* showing the distribution of calcite and aragonite in three dimensions. Slabs are shown consecutively from the apex or posterior end to the anterior, and are spaced approximately 2 to 3 cm apart.

Internal Sediments

Sponge borings in *Strombus gigas* contain poorly lithified to indurated internal sediments that are highly variable in terms of their distribution, amount, composition, grain size, and sorting (Figure III-2). The composition, grain size, and sorting vary according to the locality from which the sample was collected; however, the amount of sediment varies between samples from the same location and between adjacent borings in the same shell.

Composition and Distribution

The allochems present in sponge borings include partly altered and unaltered skeletal fragments and peloids, 50 μm to 1mm long (Plate III-1C). Skeletal grains include fragments of molluscs (particularly bivalves), corals, *Halimeda*, red algae, echinoids, foraminifera (especially peneroplids), and tunicate spicules. Jones (1990) provided detailed morphological description of these spicules and their syntaxial overgrowths. The peloids include extensively micritized and recrystallized skeletal fragments, as well as fecal pellets, as indicated by the presence of canal systems. Skeletal fragments are generally rounded to well rounded; however, shells collected from bivalve facies A and B contain allochems that are significantly more angular than those of other localities. The variability in the roundness of the allochems is a function of the nature of the depositional facies from which the shell was collected.

The allochems are commonly encased by micritic coatings 10 μm to 30 μm in thickness. Examination of these micrite coatings at high magnification shows that in some grains, the contact between the micrite and the allochem is diffuse, and the micrite layer appears to represent an altered rim of the allochem. More commonly, the contact between the micrite and the allochem is sharp, and the coating is irregular in thickness, indicating that the micrite is a cement coating. On some allochems, particularly those that are not sheltered by other grains, the micrite cement coating on the upper surface of the particle is slightly thicker than that on the underside (Figure III-2D).

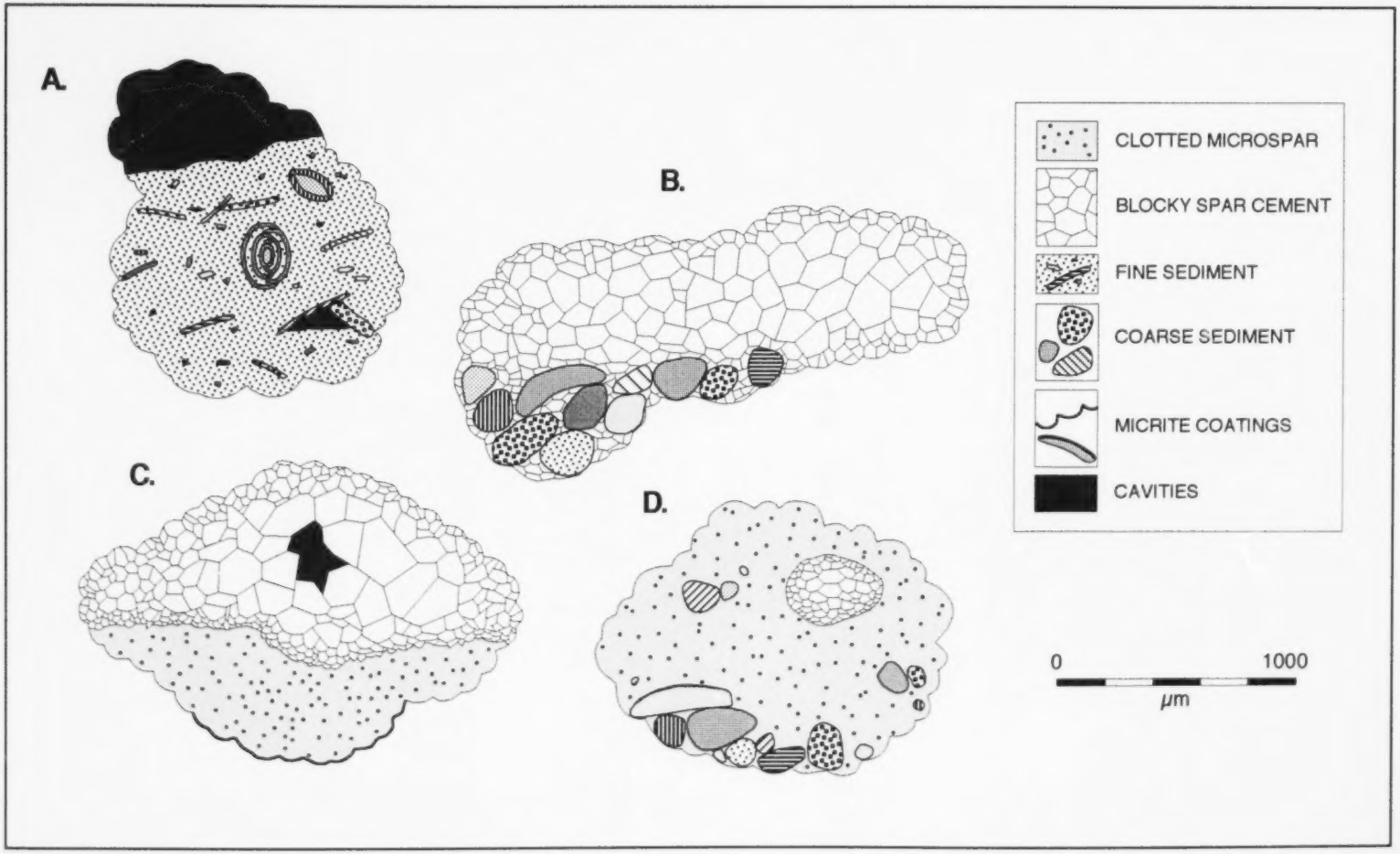


Figure III-2. Schematic diagram of typical sediment/cement distributions within sponge borings in *Strombus gigas*.

Internal sediments are commonly geopetal (Figure III-2B), cemented or uncemented, and occur in conjunction with a variety of cement types. Internal sediments are most abundant in the borings closest to the shell edge; however, their distribution and amount varies greatly between adjacent cavities of the same shell. Some borings are almost entirely filled with internal sediment whereas adjacent cavities are empty, or contain only cement.

Grain Size and Sorting

The internal sediment ranges from micrite to coarse, skeletal fragments and peloids 50 to 500 μm long. Rare, larger grains up to 1 mm are present. The degree of sorting ranges from poor to good. In some borings micrite supports larger grains 30 to 150 μm long (Figure III-2A). Elsewhere, the sediment consists entirely of large grains 150 to 500 μm long (Figure III-2B).

The size and sorting of grains in sponge borings is controlled by the size, orientation, and configuration of borings and their apertures. Large borings, that are well connected to the shell edge and have large apertures, are dominated by coarse allochems, that occur alone or in conjunction with smaller particles. By contrast, smaller, more isolated cavities are empty or contain only fine-grained internal sediment.

Cements

Sponge borings in *Strombus gigas* contain, in order of abundance, (i) blocky calcite spar, (ii) pelsparite, (iii) micrite coatings on the walls of the borings and allochems, and/or (iv) needle fibre calcite. All four of these cement types may be present in an individual boring; however, it is common for one or more of these cements to be absent.

Blocky Calcite Spar

Blocky calcite spar is common in borings of shells collected from patch reefs (coral facies A) and the reef tract (coral facies B), and less abundant in samples from quiet water lagoonal environments (bivalve facies A and B). Borings may be totally occluded by blocky calcite spar or they may be lined with spar cement and have pore space remaining in their interiors. Commonly, blocky calcite fills or lines the upper part of a cavity that contains geopetal sediment (Figure III-2B) or pelsparite (Figure III-2C; Plate III-1D).

Crystals of blocky calcite spar cement are typically 20 to 150 μm long (average 75 μm); however, in extreme cases, individual crystals are up to 500 μm long. Crystals are predominantly equant (Plate III-1D); however, they are sometimes elongate. Where there is a dominance of non-equant crystals, there is a preferred orientation of the longest axis normal to the wall of the boring. Intercrystalline boundaries are planar. Some borings show a significant increase in crystal size towards the center of the pore (Figure III-2B; 2C), whereas others contain cement crystals that are all approximately the same size.

Growth banding, in the form of regular, straight bands 3 to 6 μm wide, is evident in samples that have been lightly etched in HCl and examined on the SEM (Plate III-1E). The growth zones are defined by differences in relief on the surface of the cement crystal, and are presumably related to slight variations in the solubilities of adjacent zones. Growth bands can be traced across intercrystalline boundaries into adjacent cement crystals. Interfaces between adjacent zones mark the former positions of old crystal faces, thus zoning documents the growth history of the crystals.

Pelsparite

A relatively common type of cement in sponge borings consists of dense spherical to subspherical aggregates of micrite 20 to 50 μm in diameter ('floating peloids' of Macintyre 1985) surrounded by equant crystals, 4 to 15 μm wide (Plate III-1F). The edges of the

'floating peloids' are poorly defined, and have surfaces that are transitional with the microspar that surrounds them.

Pelsparite cement may accumulate as a geopetal fill in the lower portion of a cavity (Figure III-2C; Plate III-1D), fill the cavity entirely, or have an irregular distribution, in which most of the cement adheres to cavity walls, but irregularly distributed and shaped pockets of pore space remain. Pores in the pelsparite are commonly filled with blocky calcite spar (Figure III-2D). Where pelsparite occupies the lower portion of a boring, it is commonly overlain by blocky calcite spar (Figure III-2C). The boundary between pelsparite and coarser spar is either diffuse or sharp. Pelsparite cement commonly incorporates allochems such as mollusc fragments, *Halimeda*, coral fragments and foraminifera (Figure III-2D).

Micrite Coatings

The walls of sponge borings in *Strombus gigas* are commonly lined with a layer of dense fluorescent micrite, 10 to 45 μm thick (average 15 μm). These coatings, formed of subequant rhombs, are petrographically similar to the micrite cement coatings that encase skeletal fragments and other allochems. Micrite coatings are commonly slightly thicker along the basal surface of the boring (Figure III-2C). They commonly appear lumpy and clotted, perhaps due to the incorporation of allochems or 'floating peloids', 5 to 15 μm long. Such linings commonly show partial alteration to coarser spar crystals, 5 to 10 μm long.

Needle Fibre Calcite

A relatively rare variety of cement in sponge borings consists of elongate crystals 2 to 4 μm wide, and 10 to 40 μm long (Plate III-1G). Following the terminology of Folk (1965, p. 25), these crystals are referred to as 'needle fibres'. This type of cement occurs

as scattered randomly oriented crystals, and less commonly, as loose fibrous mats and tangential needle fibres.

Discussion

Origin and Occurrence of Sponge Borings

The boring action of sponges is accomplished by chemical dissolution of the substrate (Cobb 1969; Rutzler and Rieger 1973; Rutzler 1974, 1975; Pomponi 1977; Acker and Risk 1985) and the eventual removal of hemispherical chips 40 to 60 μm in diameter. Boring sponges possess specialized etching cells or amoebocytes that release a substance (possibly carbonic anhydrase - Rutzler 1975) that isolates and then separates a chip from the substrate. Although a chemical mechanism of boring implies that much of the substrate is chemically dissolved, it is estimated that only 2 to 3% of the excavated material is removed in solution (Warburton 1958; Rutzler and Rieger 1973).

The dominant product of the dissolution process is the creation of particles with rounded to oval or elongate outlines, that have a single large convex basal surface and up to ten concave side or roof surfaces (Futterer 1974; Ekdale *et al.* 1984). The characteristic morphology of carbonate chips produced by boring sponges is recognized in the fine fraction of many sediments in both modern and ancient regimes. The proportion of modern reef sediments attributed to bioerosion by sponges is estimated at 2 to 3% in the Persian Gulf and northern Adriatic Sea (Futterer 1974), 30% at Fanning Island (Futterer 1974), and 40% on the Bermuda Platform (Rutzler 1975).

The amount of shell material removed by bioeroders from Pleistocene samples of *Strombus gigas* ranges from 0 to 38% by volume and averages 11% (Table III-1). The degree of boring in *Strombus gigas* from lagoonal and inter-reef environments is variable (Figure III-3), and reflects localized differences in the abundance of bioeroders and the length of time over which they affected the shell. *Strombus gigas* from reef tract and reef channel environments contain a significantly lower proportion of borings compared to their

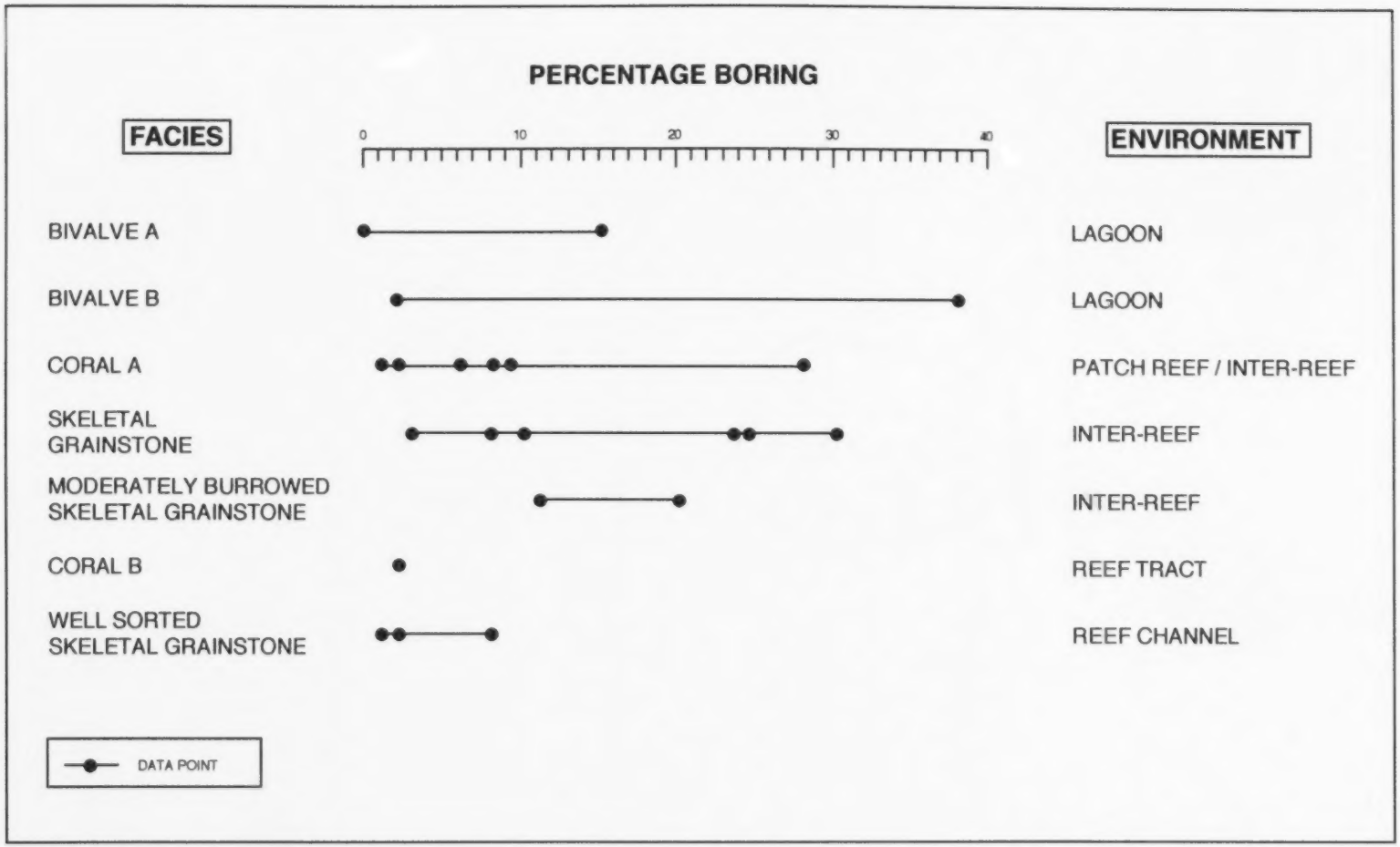


Figure III-3. Percentage boring in *Strombus gigas* for facies of the Ironshore Formation. Facies and environments from Hunter and Jones (1989).

lagoonal and inter-reef counterparts (Figure III-3). This might be explained by higher energy conditions, because the colonization of a shell or other substrate by sponges is strongly influenced by the hydrodynamic regime, particularly at the free swimming larval stage (Lawrence 1969).

Composition, Grain Size and Sorting of Internal Sediments

The internal sediments of sponge borings in *Strombus gigas* are similar in composition, grain size, and sorting to the rock and poorly lithified sediment that encases the shell. For example, shells of *Strombus gigas* from areas dominated by poorly sorted skeletal wackestones and packstones of bivalve facies A and B, contain internal sediments formed of fragmented bivalves, gastropods, foraminifera, and corals mixed with very fine- to fine-grained non-skeletal carbonate particles. Similarly, shells from coral facies A and B contain internal sediments characterized by numerous altered and unaltered, medium- to coarse-grained coral fragments. In general, the lithological and compositional characteristics of internal sediments in shells from various localities are consistent with the facies descriptions of Hunter and Jones (1989) for those localities (Table I-1). The upper size range of the grains is typically not represented in the borings due to the restrictive nature of the configuration and size of pore apertures (Ginsburg 1973; Scoffin and Garret 1974).

Origin of Cements

Sponge borings in *Strombus gigas* contain micrite cement, pelsparite, blocky calcite spar and needle fibre calcite cements. Regardless of which types of cement are present in an individual boring, the sequential order of precipitation of these phases was constant (Figure III-4). Petrographic evidence indicates that filling of the borings with sediment may occur before, during, or after precipitation of micrite coatings and pelsparite, but always predates blocky calcite spar and needle fibre calcite.

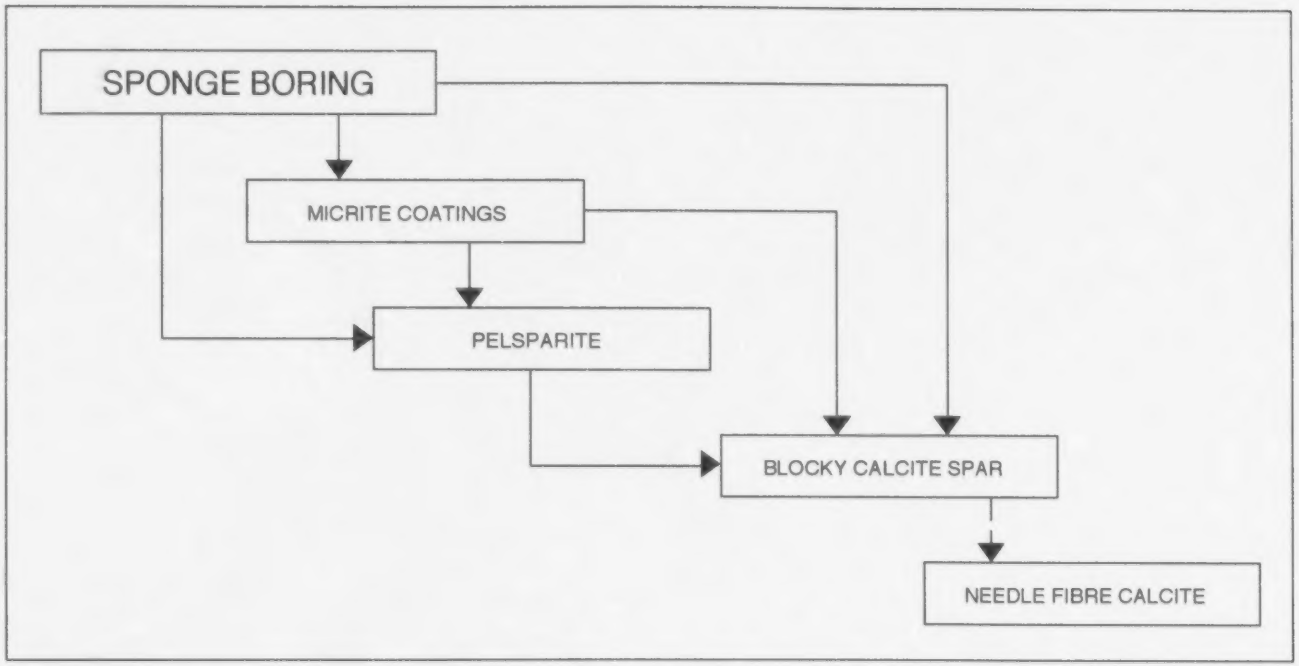


Figure III-4. Schematic diagram of possible cement sequences in sponge borings in *Strombus gigas*. Note that filling of the borings with sediment may occur before, during or after precipitation of micrite coatings and pelsparite, but always predates blocky calcite spar and needle fibre calcite.

Blocky Calcite Spar

Blocky calcite spar is volumetrically the most important cement in the sponge borings. Due to its coarse crystal size and predominantly equant habit, it is considered to be diagnostic of freshwater meteoric diagenesis (Bathurst 1975; Longman 1980; James and Choquette 1984). Although high magnesium calcite cements are precipitated in submarine settings, the morphology and size of submarine calcite differs from calcite cements precipitated in the meteoric environment. Submarine calcite cements are dominantly micrite (James and Choquette 1983), but fibrous to bladed cystals less than 100 μm long are also common (James *et al.* 1976; James and Ginsburg 1979; Marshall and Davies 1981; Aissaoui *et al.* 1986). Rare equant crystals of calcite, 20 to 50 μm wide, occur locally in hardgrounds and reefs (James and Choquette 1983).

Borings in shells that are dominantly aragonite contain significantly lower proportions of blocky calcite spar than do highly calcitized samples. The correlation between low degree of calcite cementation and low degree of mineralogical alteration indicates that, for these samples, circulation of meteoric fluids saturated with respect to calcite was inhibited.

Pelsparite

Pelsparite in sponge borings in *Strombus gigas* is texturally similar to that described from modern reefs (Ginsburg *et al.* 1971; Land 1971; Friedman *et al.* 1974; Scherer 1974; James *et al.* 1976; Macintyre 1977; Alexandersson 1978; Macintyre 1985; Chafetz 1986). It is abundant in modern reefs, particularly in isolated and semi-isolated reef cavities, and as surface crusts on framework components. Despite evidence that pelsparite forms in marine environments, similar textures can occur in vadose settings (Jones 1989). This suggests that either marine waters are not essential to the formation of these textures, or that periodic or repeated incursions of marine water into vadose environments may produce petrographically identical features (Jones 1989).

Pelsparite cements in modern reefs contain elliptical to spherical peloids, 15 to 60 μm in diameter, that consist of a dense micritic nucleus and a more coarsely crystalline rim. The mechanism by which these marine peloids form is controversial. The proposed origins for these peloids include:

1. replacement texture (Taylor and Illing 1969; Shinn 1969),
2. fecal pellets (Macintyre *et al.* 1968; Land and Goreau 1970; Land and Moore 1980),
3. detrital grains (James *et al.* 1976),
4. calcified algal filaments (Schroeder 1972; Ginsburg and Schroeder 1973; Friedman *et al.* 1974),
5. crustose coralline algae (Gvirtzman and Friedman 1977),
6. inorganic cement precipitates (Alexandersson 1972*a*, 1972*b*; Macintyre 1977; Marshall and Davies 1981; Marshall 1983; Lighty 1985; Macintyre 1985), and
7. bacterially induced precipitates (Macintyre and Videtich 1979; Chafetz 1986).

Early interpretations of peloidal textures in marine reef rock suggested that the peloids represent existing carbonate grains or organic structures that were altered and/or incorporated into the cement during its precipitation. As the widespread occurrence of submarine cements in modern reefs became known, it was accepted that the peloids precipitated directly from sea water. This view is currently held as the most viable mechanism for marine peloid formation; however, the degree to which nucleation is organically induced and/or controlled has not been established.

Chafetz (1986) presented evidence that the cores of the peloids are composed of fossil bacterial clumps. Alternatively, inorganic precipitation may occur through intermediate growth stages (Alexandersson 1972*b*, 1978), repeated nucleation (Macintyre 1977, 1985), spontaneous nucleation (Marshall 1983), or crystal growth on nuclei of silt-sized clastic detritus (James *et al.* 1976). The difference in texture between the nucleus and rim of the peloids suggests that the dentate rim of the peloids represents a secondary stage of slower

and more organized precipitation of coarser euhedral calcite (Macintyre and Marshall 1988; Macintyre 1977; Marshall 1983; Chafetz 1986).

The process of spontaneous nucleation as outlined by Marshall (1983) involves peloid nucleation in pore waters, and gradual enlargement of the peloids through successive precipitation of micrite until they reach a critical size and settle on the floor of the cavity. Such a process would account for the geopetal accumulation of pelsparite in sponge borings.

The inclusion of mollusc and coral fragments, *Halimeda*, and foraminifera in the pelsparite indicates that it precipitated in the submarine environment concurrent with accumulation of internal sediment in the borings. The submarine origin of this cement is further substantiated by the fact that, based on petrographic evidence, it predates the meteoric precipitation of blocky calcite spar.

Micrite Coatings

A wide spectrum of processes is known or inferred to be responsible for the formation of micrite coatings on the surfaces of skeletal and non-skeletal components and cavities. These include:

1. destructively generated micrite 'envelopes' produced in the submarine environment by centripetal replacement of aragonitic material by precipitation of micritic magnesium calcite in boring tubes vacated by algae (Bathurst 1966; Winland 1968), fungi, and bacteria (Friedman *et al.* 1971),
2. micritization in the marine environment by dissolution/reprecipitation in an organic mucilaginous sheath (Kendall and Skipworth 1969),
3. submarine cement precipitated on grains and skeletal surfaces as a rind of magnesium calcite micrite (Ginsburg *et al.* 1971; Ginsburg and Schroeder 1973; Macintyre and Marshall 1988),

4. constructively generated micrite coatings produced by coalescence of calcified filaments of the marine algae *Ostreobium* and associated precipitation of micrite and microspar cement inside the pores (Kobluk and Risk 1977*a*, 1977*b*), and
5. constructive micrite coatings formed in the near-surface, vadose diagenetic environment due to colonization of grain surfaces by algae and fungi, calcification of their filaments, and precipitation of micrite cement (James 1972*b*; Calvet 1982; Jones 1987).

Although micrite coatings form by a variety of processes, in the shallow marine and vadose diagenetic environments, the mechanism by which the coatings have been created can be determined from detailed examination of the coatings at high magnification. Steinen (1974) presented textural criteria for distinguishing inorganically precipitated micrite cements from coatings or envelopes formed by processes related to the activity of micro-organisms. Petrographically, an inorganic origin for micrite coatings is confirmed if:

1. the contact of the substrate with the micrite cement is sharp in contrast to the diffuse or ragged appearance of micrite coatings associated with boring algae or micritized grain boundaries,
2. texturally, the micrite represents a coating on the surface of the substrate rather than an altered rim of the substrate, and
3. "...relict cellular or laminar structures suggestive of algae are absent" (p. 1016).

In *Strombus gigas*, most micrite coatings on the walls of borings and surfaces of allochems show no evidence of association with micro-organisms. Contact between the micrite and the substrate is sharp, and the micrite does not appear to be an altered rim of the wall of the boring or allochem. This evidence indicates that most of the micrite coatings are true inorganic cement precipitates.

As determined petrographically, micrite coatings usually predate the precipitation of the pelsparite cement, suggesting that they are predominantly marine in origin. The increase in thickness of the coatings on the upper surfaces of allochems and along the basal portion of borings, indicates that micrite may nucleate from pore waters and then settle, in a

manner similar to that discussed above for the formation of peloids. Some of the micrite may have been precipitated in the vadose diagenetic environment, but the relative importance of vadose micrite compared to marine micrite is extremely difficult to assess from petrographic evidence.

Regardless of their origin, micrite coatings are more resistant to dissolution than the aragonite interiors of the skeletal or non-skeletal material they encase, thus they allow for the preservation of original shapes of skeletal particles, borings or any surface they coat (Friedman *et al.* 1971; James and Choquette 1984).

Needle Fibre Calcite

Needle fibre cements have been described from the Pleistocene of Barbados (James 1972*a*, 1972*b*; Steinen 1974; Harrison 1974, 1977), Pleistocene eolianites from Mallorca, Spain (Calvet 1982), Holocene and Pleistocene eolianites from Yucatan (Ward 1970, 1975), subsurface Bahamian calcarenites ('whisker crystals' - Supko 1971), and the Pleistocene of Cayman Brac (Jones and Ng 1988). Needle fibre calcite is indicative of vadose precipitation, and is commonly associated with surficial calcareous crusts and rhizoliths. They typically form fibrous mats of tangentially and/or randomly oriented crystals that have accumulated as sheaths around rootlets. Ward (1970) suggested that these crystals formed by calcite precipitation along or in fungal hyphae. Alternatively, James (1972*a*, 1972*b*) argued that they are the result of inorganic precipitation from supersaturated vadose waters near the subaerial subsurface.

Needle fibre mats in the Pleistocene of Barbados are commonly associated with "...irregularly shaped areas which may be dissolution enlarged channelways" (Steinen 1974, p. 1014). Such channelways probably represent paths of least resistance for rootlets. Steinen (1974) also noted that needle fibre crystals are present only in rocks that have been exposed exclusively to vadose diagenesis, and are not preserved in samples that

have been alternately subjected to vadose and phreatic processes. Evidently these needle fibre crystals are unable to survive in the freshwater phreatic environment.

Needle fibre calcite is a relatively rare type of cement in sponge borings, but where present, it is always the last phase of cementation. These crystals probably formed in the near-surface vadose environment in association with penetration of roots and rootlets into the formation.

Cement Distribution

Cement type and abundance varies between localities and between adjacent borings of the same shell. Despite this, the paragenetic sequence of cements is constant (Figure III-4). Cementation in sponge borings in *Strombus gigas* proceeded by:

1. submarine precipitation of micrite cement on the walls of borings and allochems,
2. submarine precipitation of pelsparite,
3. vadose (and freshwater phreatic?) precipitation of blocky calcite spar, and
4. vadose precipitation of needle fibre calcite.

The type and amount of cement in sponge borings was controlled in part by depositional environment. The abundance of micrite coatings and needle fibre cement shows no apparent correlation to sedimentary facies, however the distribution of blocky calcite spar and pelsparite can be explained in terms of the hydrologic regime responsible for depositional and diagenetic processes.

Blocky calcite spar and pelsparite are most abundant in shells collected from patch reefs (coral facies A) and the reef tract (coral facies B). By contrast, shells from quiet water lagoonal environments (bivalve facies A and B) contain a relatively low proportion of blocky calcite spar and virtually no pelsparite. The lack of pelsparite in the lagoonal deposits can be attributed to the relatively poor circulation of marine waters through pore spaces. As shown by studies of modern marine environments, submarine cementation is most pronounced along the seaward margins of reefs and is not a significant factor in the

lithification of finer-grained back reef deposits that are protected from wave action. By contrast, the reef tract and patch reefs formed under higher energy conditions that allowed a greater degree of fluid circulation in pores, necessary for the precipitation of large volumes of cement.

Blocky calcite spar is most abundant in shells of *Strombus gigas* collected from localities characterized by coral floatstones and boundstones that have significantly higher porosity and permeability than their lagoonal counterparts. This higher porosity and permeability has allowed significant volumes of meteoric waters to pass through them, thus they contain higher proportions of meteoric cement.

B. MINERALOGICAL ALTERATION OF THE SHELL

The degree of alteration of aragonite to calcite in the shell of *Strombus gigas* is highly variable (Table III-1). The suite of samples examined includes shells in all stages of alteration, ranging from unaltered to completely replaced (Figure III-5). The intensity of replacement by calcite shows no significant correlation to depositional facies (Figure III-5) or geographical location.

Textural and Mineralogical Relationships

Calcite is typically concentrated along the outer edge of the shell where boring is most intense, and in the interior of the columella (Figure III-1; Plate III-2). There is little or no difference in the intensity of alteration from the anterior to posterior ends of the shell (Figure III-1). In addition, isolated irregularly shaped patches of calcite also occur throughout the shell and appear to float in unaltered aragonite (Plate III-2).

Altered portions of the shell consist of an interlocking mosaic of elongate to subequant, anhedral calcite crystals (Plate III-3A; 3B). Intercrystalline boundaries are ragged and uneven, and enfacial junctions (triple junctions with one angle equal to 180°) are rare. Calcite crystals end sharply at the shell edge, and do not extend into surrounding

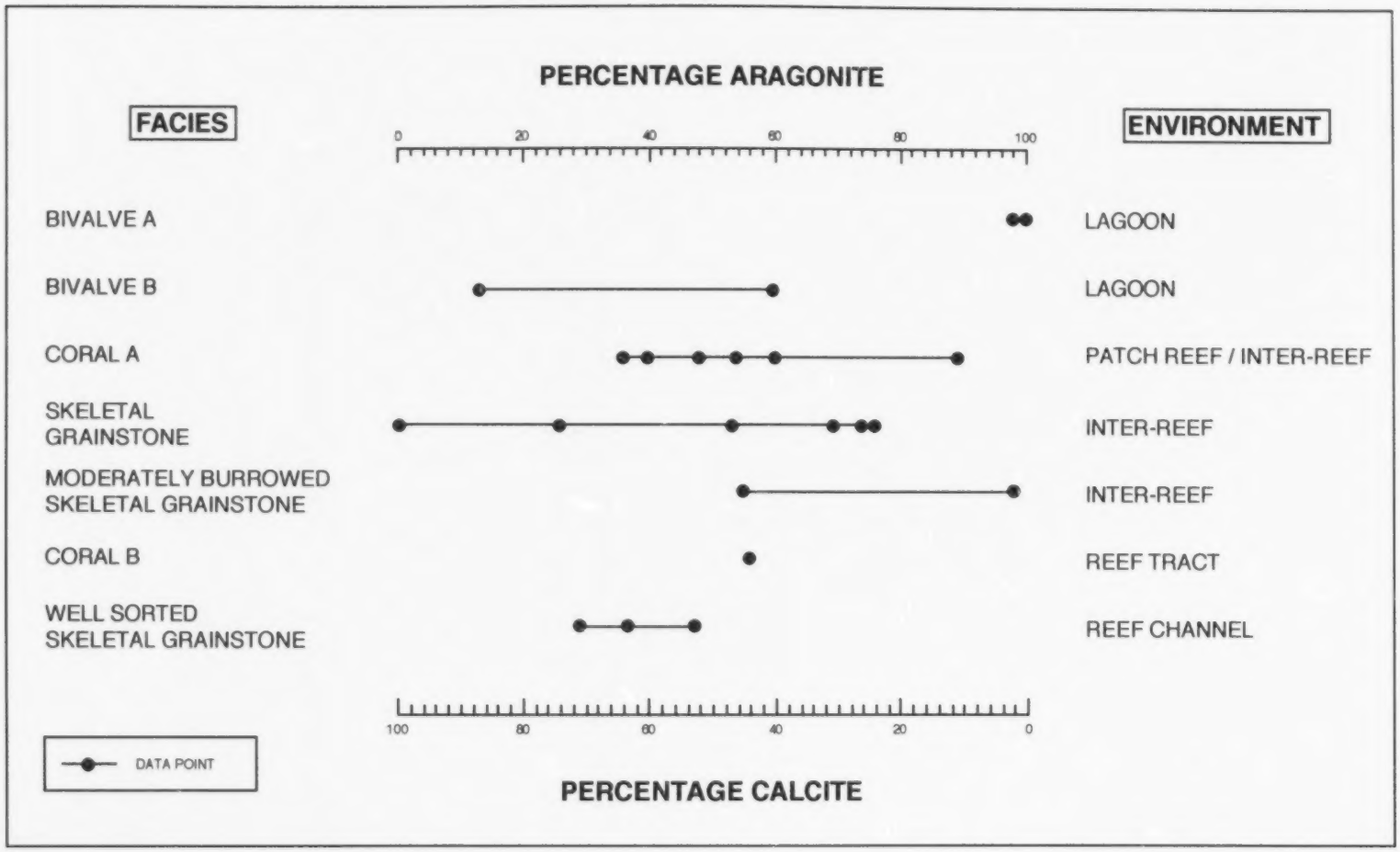


Figure III-5. Relative proportions of aragonite and calcite in *Strombus gigas* for facies of the Ironshore Formation. Facies and environments from Hunter and Jones (1989).

Plate III-2

Photograph of a thin section through the columella of *Strombus gigas*. The original shell is aragonite (a) with crossed-lamellar structure, and is partly replaced by elongate to subequant, anhedral crystals of calcite (c). Calcite is concentrated in the interior of the columella, and along the outer edge of the shell where borings (b) are abundant (#2614, Loc. M).

b
a
b
c
a
5 mm

Plate III-3

Alteration of the aragonitic shell of *Strombus gigas* to calcite.

(A) Thin section photomicrograph of the interlocking mosaic of calcite that replaces the shell. The mosaic consists of elongate to subequant, anhedral crystals. Intercrystalline boundaries are ragged and uneven and enfacial junctions are rare (#2094, Loc. H).

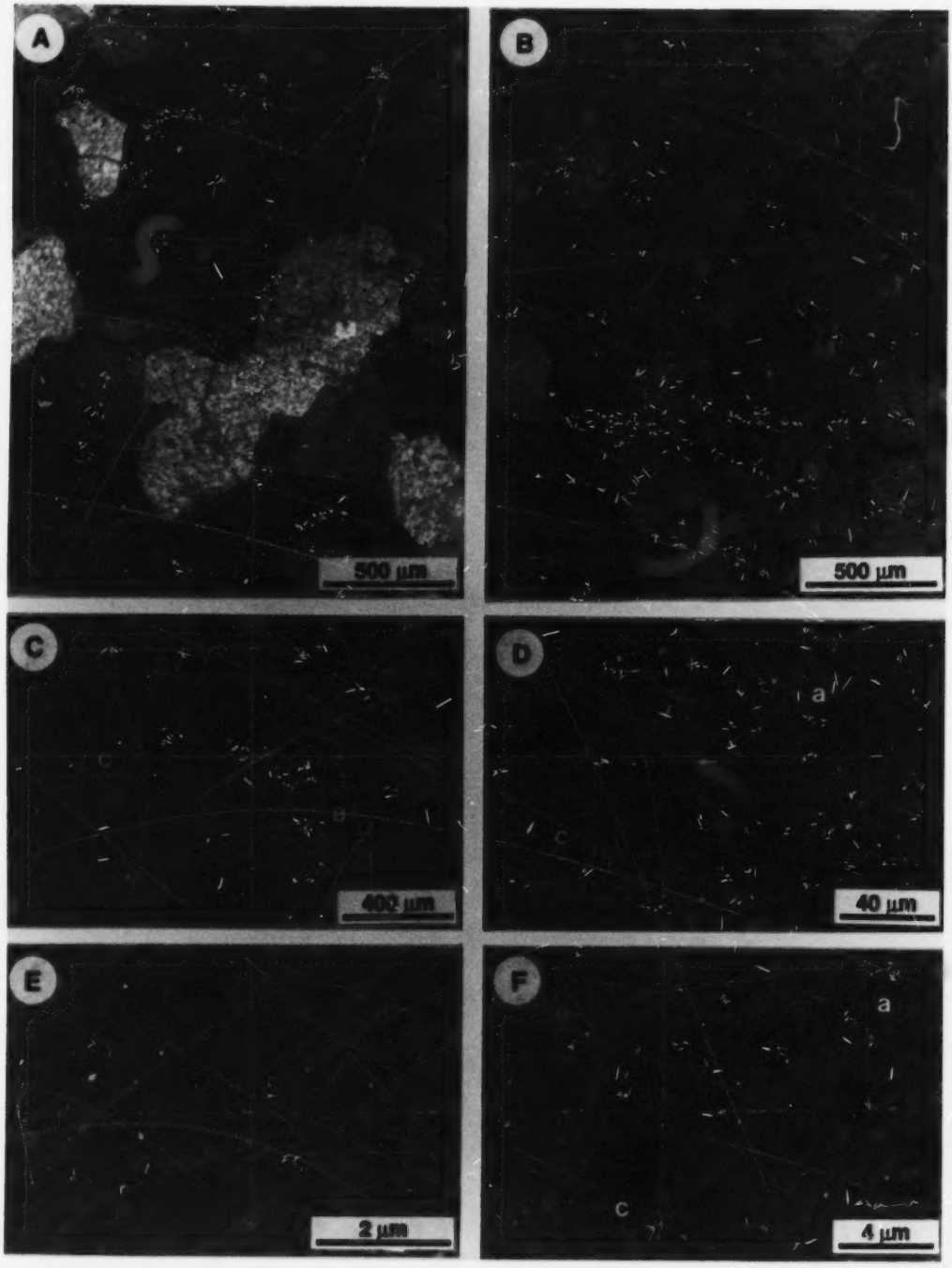
(B) View as above (#2094, Loc. H).

(C) SEM photomicrograph of the boundary between aragonite (a) and calcite (c). The contact is an irregular surface, except where it is controlled by boundaries in the original aragonitic shell. Relict crossed-lamellar structure is preserved in the calcite mosaic (#1439, Loc. B).

(D) Detailed view of the boundary between calcite (c) and aragonite (a). Note that there is no pore space visible at the boundary (arrow) between the two phases (#1439, Loc. B).

(E) SEM photomicrograph of relict rod-shaped aragonite crystals (#1963, Loc. MOS).

(F) SEM photomicrograph of the contact between aragonite (a) and calcite (c). The orientation of aragonite inclusions in calcite is identical to that of aragonite crystals in the adjacent crossed-lamellar structure. The abundance of aragonite inclusions decreases away from the aragonite/calcite contact (#1963, Loc. MOS).


A
500 µm
B
500 µm
C
400 µm
D
a
c
40 µm
E
2 µm
F
a
c
4 µm

sediment or sponge borings ('fabric selective mosaic' of Pingitore 1976). Maximum crystal size occurs in the columella, where individual calcite crystals are up to 7 mm long. Many large calcite crystals appear to be composed of small subcrystals with slightly different extinction positions.

The contact between aragonite and calcite is sharp but irregular or jagged (Plate III-3C). Commonly, the calcite mosaic extends into aragonite along intercrystalline boundaries between calcite crystals. No pore space is visible along the aragonite/calcite contact (Plate III-3D). Floating patches of unaltered aragonite may be completely surrounded by calcite, but more commonly it is calcite that is included in aragonite.

The distribution and texture of the calcite mosaic is controlled by the original structure of the aragonitic shell, and the secondary development of cavities by boring sponges. Primary crossed-lamellar structure and original boundaries between shell layers are of utmost importance in influencing the texture of the replacement product, and as such, are commonly preserved as relics in the calcite that replaces the shell. Sponge borings are a significant control in that their presence or absence dictates the manner in which replacement proceeds. By controlling the nature of the diagenetic process, sponge borings exert an influence on resultant fabrics.

In thin section, relict aragonite microstructure is preserved as parallel lines of inclusions in the calcite mosaic, that continue without deviation across intercrystalline boundaries (Plate III-3C; 3D). The orientation of these rows of inclusions is identical to the orientation of first order lamellae in the adjacent aragonite. Examination on the SEM shows that these inclusions are rod-shaped aragonite crystals identical to those in the crossed-lamellar structure (Plate III-3E). These crystals are preserved as relics in the calcite, up to a maximum distance of 1 mm from the aragonite/calcite contact (Plate III-3F). Preservation of these oriented inclusions results in a calcite mosaic that mimics the crossed-lamellar structure of the aragonite. First order lamellae in the unreplaced aragonite can be traced across the boundary into the calcite mosaic, where they are defined by the orientation

of relict inclusions. Alternate zones in the calcite are coincident with adjacent lamellae in the aragonite, and the orientation of aragonite crystals in corresponding zones on either side of the boundary is identical. Relict lamellae in the calcite are therefore defined by differences in the orientation of relict aragonite crystals.

Original boundaries between the four layers of the shell control both the distribution and texture of the calcite. Commonly these boundaries act as barriers to replacement such that the calcite mosaic ends sharply along this contact, and individual calcite crystals terminate against the edge. Where this occurs, the crystal face in contact with the primary boundary follows this surface and is planar to slightly curved. Where the calcite mosaic transects two adjacent shell layers, crystals of calcite on either side of the boundary meet along a planar surface (Plate III-4A).

Textural evidence indicates that sponge borings are critical in controlling the nature of aragonite to calcite alteration. Calcite crystals along the margins of sponge borings are typically elongate and oriented perpendicular to the margin of the boring (Plate III-4B; 4C). This results in a radial fabric that displays a distinctive increase in crystal size outwards (Plate III-4C). In the area between two or more adjacent borings, the surface along which the radial fabrics from each boring meet can be identified as a compromise boundary (Plate III-4D).

Shells of *Strombus gigas* that have undergone only slight mineralogical alteration, show preferential replacement of the aragonite surrounding the borings, such that calcite forms rings around the borings. This association of sponge borings and replacement is so prevalent that, in partly altered shells, the zones around the borings are wholly calcite. In rare samples that show no alteration to calcite (e.g. 2207 A; Table III-1), the aragonite that surrounds the borings is distorted or discolored. Although these 'alteration halos' are common in shells that contain no calcite, they are not present in aragonitic zones of partly altered shells.

Plate III-4

Textural characteristics of the calcite mosaic in *Strombus gigas*.

(A) Thin section photomicrograph showing how original shell boundaries control the distribution and texture of replacement calcite (a = aragonite, b = boring,c = calcite). Organic rich surfaces between shell layers commonly separate replaced and unreplaced portions of the shell. Where the calcite mosaic transects shell layers (arrow), intercrystalline boundaries between calcite crystals on either side are commonly planar (#1893, Loc. MOA).

(B) Thin section photomicrograph of the radial fabric of the calcite mosaic around sponge borings (b). Calcite crystals are elongate and oriented perpendicular to the borings (#2094, Loc. H).

(C) Thin section photomicrograph showing the increase in crystal size of replacement calcite away from borings (b) in the shell (#2926, Loc. SHB).

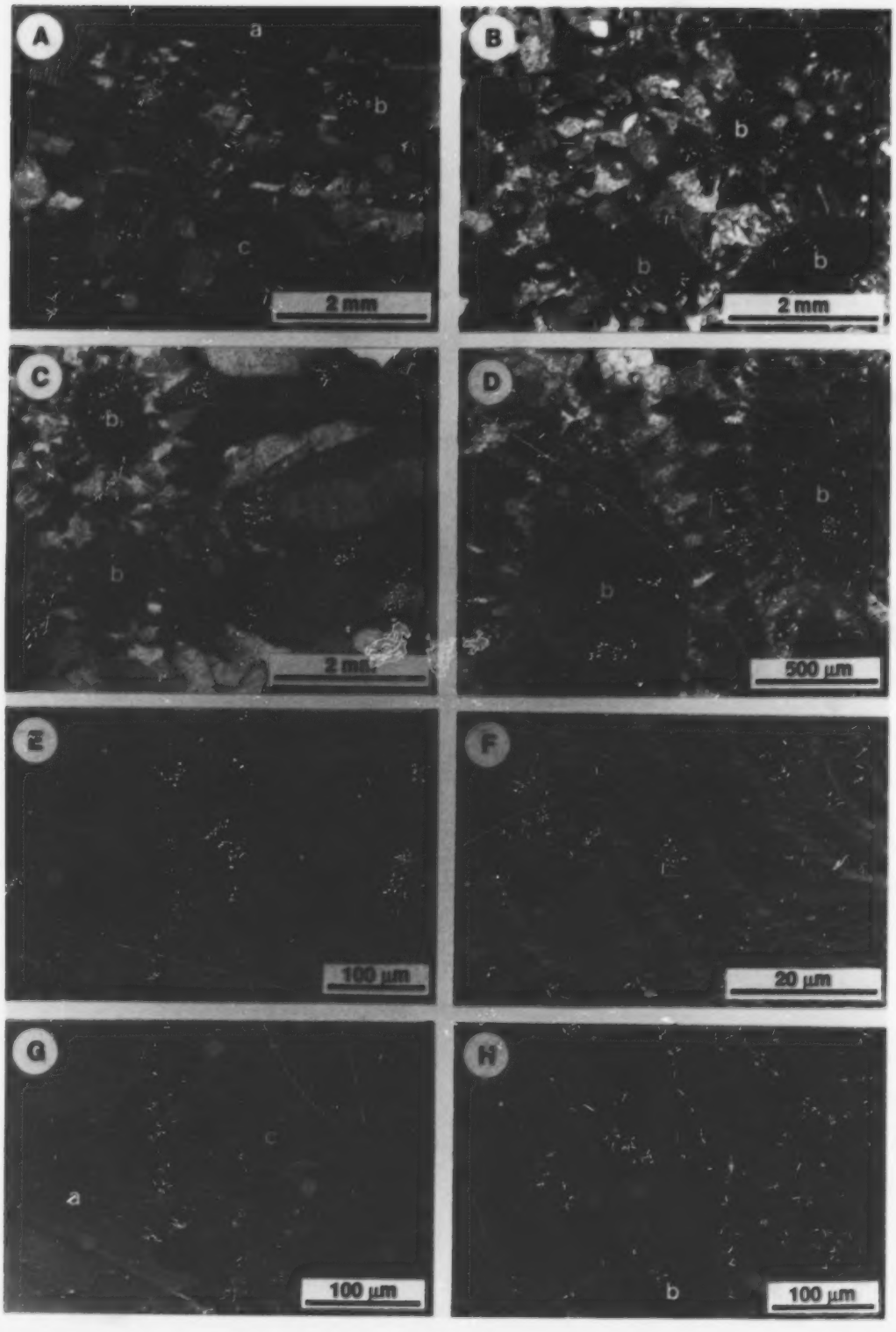
(D) Comprise boundary (arrow) between calcite crystals that radiate outwards from two adjacent borings (b) (#2094, Loc. H).

(E) SEM photomicrograph of curved subparallel growth bands in neomorphic calcite (#1963, Loc. MOS).

(F) Detailed view of growth zones in neomorphic calcite (#1963, Loc. MOS).

(G) SEM photomicrograph showing the progression of growth zones in neomorphic calcite (c) towards unaltered aragonite (a) (#1963, Loc. MOS).

(H) Comparison between growth zones in neomorphic calcite, and those of blocky calcite cement. Growth zones in the cement that lines the boring (b) are more regular and straight, and are thinner than zones in the neomorphic calcite. Note that along the margin of the boring (arrow), intercrystalline boundaries between neomorphic calcite and calcite cement are commonly coincident (#1963, Loc. MOS).


A
a
b
c
2 mm
B
b
b
b
2 mm
C
b
b
2 mm
D
b
b
500 µm
E
100 µm
F
20 µm
G
c
a
100 µm
H
b
100 µm

Examination of the neomorphic spar at high magnification (SEM) reveals that many of the neomorphic crystals are zoned, a feature that has not been documented previously. These zones consist of gently curving subparallel bands, 5 to 10 μm wide (Plate III-4E; 4F), that are continuous across intercrystalline boundaries in the mosaic. The progression of zones in neomorphic calcite radiates outwards from sponge borings in the direction of unaltered aragonite (Plate III-4G). Where zoned neomorphic crystals lie adjacent to zoned calcite cement in the borings, intercrystalline boundaries on either side of the margin of the boring are commonly coincident (Plate III-4H).

A comparison of zones in neomorphic calcite and growth bands in calcite cement reveals two important differences:

1. growth zones in cement are more regular and straighter than those of neomorphic calcite, and
2. zones in neomorphic spar are wider (5 to 10 μm) than those of cement (3 to 6 μm wide).

Evidence for a Neomorphic Origin of Calcite

Bathurst (1975) suggested a number of textural criteria that could be used to differentiate neomorphic spar from pore-filling cement. Several of these textures can be cited as evidence that the calcite in shells of *Strombus gigas* is the product of *in situ* inversion of aragonite to calcite and not due to cementation in a void created by aragonite dissolution. Based on Bathurst's (1975) criteria, the neomorphic origin of calcite is substantiated because:

1. the shell is transected or wholly replaced by an interlocking mosaic of calcite crystals,
2. intercrystalline boundaries in the calcite mosaic are irregular to jagged rather than planar,
3. enfacial junctions are rare,
4. irregular patches of unaltered aragonite are completely surrounded by calcite, and
5. empty and partly filled sponge borings in the shell are preserved.

In addition to Bathurst's (1975) criteria, several additional lines of evidence can be established:

1. the texture and fabric of the calcite mosaic mimics the original microstructure of the aragonite,
2. relict aragonite crystals in the calcite have identical orientations and morphologies to that of the adjacent aragonite, and
3. growth zones, if present, are curved and irregular rather than planar.

C. DIAGENETIC MODEL

Shells of *Strombus gigas* have undergone a number of diagenetic changes in the submarine and meteoric environments (Figure III-6). Submarine modification of the shell involved:

1. encrustation and boring,
2. accumulation of internal sediments in borings,
3. precipitation of micrite cement on the walls of borings and surfaces of allochems, and
4. submarine precipitation of pelsparite cement.

Diagenetic changes in the meteoric environment included:

1. partial or complete inversion of the shell to calcite,
2. precipitation of blocky calcite cement, and
3. near-surface precipitation of needle fibre calcite cement.

Aragonite to Calcite Inversion

Where aragonite relics and original skeletal microstructure are preserved in calcite, it is evident that no appreciable void stage could have occurred during replacement. Such transformations occur by *in situ* dissolution/reprecipitation across a thin solution film (Bathurst 1964; Friedman 1964; Folk 1965; Dodd 1966; Tebbutt 1967; Kinsman 1969; Folk and Asserto 1976; Pingitore 1976; Wardlaw *et al.* 1978).

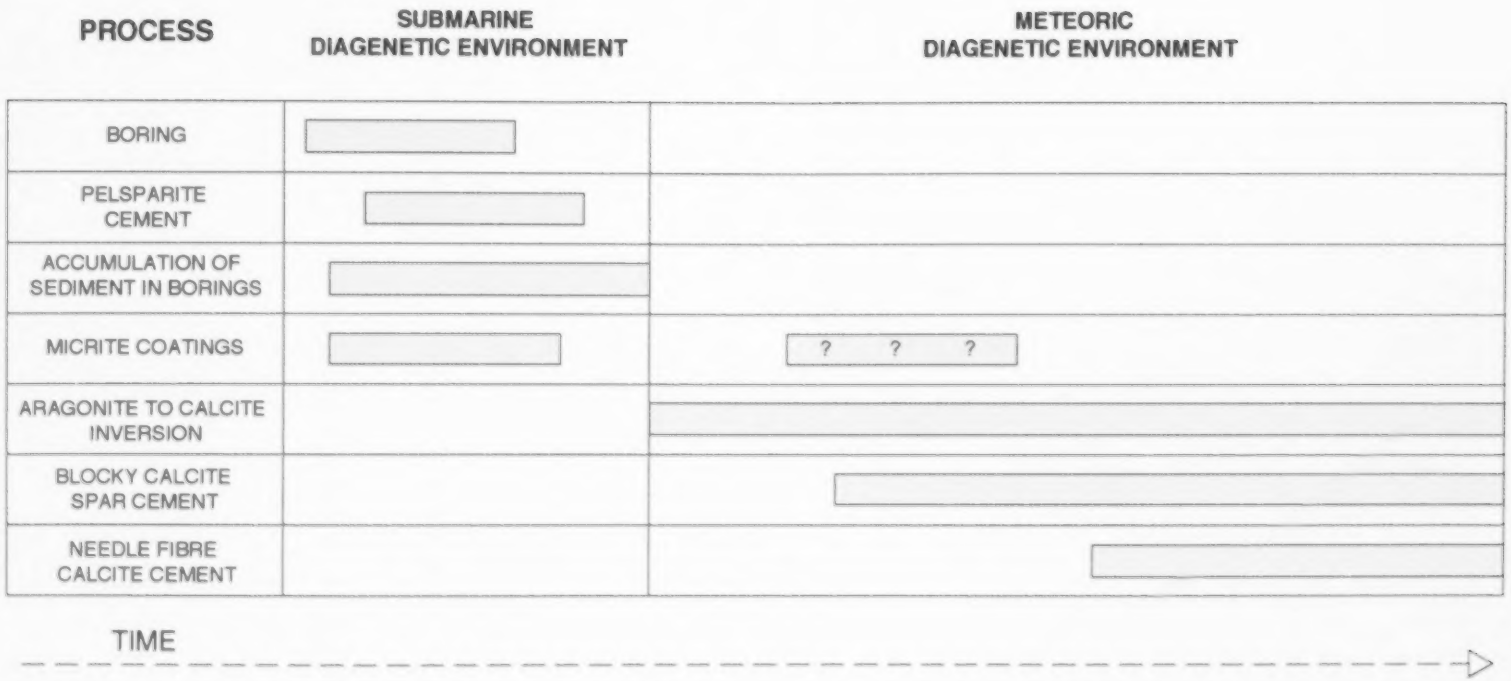


Figure III-6. Summary of the diagenetic history of *Strombus gigas*.

The model for *in situ* replacement or inversion as outlined by Kinsman (1969), involves a narrow (1 μm) crack filled with water that separates aragonite and calcite (Figure III-7). Unstable aragonite is dissolved on one side of the solution film, and calcium and carbonate ions are diffused to the other side where calcite is precipitated. Due to the solubility difference between the two polymorphs, a diffusion gradient is maintained across the film, and the process is self perpetuating. The driving mechanism for this process is the supersaturation of pore waters with respect to calcite and the undersaturation of the waters with respect to aragonite (Chave *et al*. 1962). As the dissolution/reprecipitation continues, the boundary migrates in the direction of the remaining aragonite, and aragonite is gradually replaced by calcite. The fine scale on which this process operates allows for the preservation of original skeletal microstructure and relict aragonite crystals.

Aragonite to calcite inversion in *Strombus gigas* may proceed from the shell walls inward, or be initiated along the margins of sponge borings and other primary and secondary pore space in the shell. The former process results in the neomorphic growth of a mosaic dominated by irregularly shaped crystals. Planar interfaces occur only where flat sided crystals lie against original boundaries between aragonite layers. Tebbutt (1967) described such crystals of calcite as being 'dammed' at a boundary in shell structure, as the replacement front expands laterally.

Migration of the replacement front outwards from the scalloped margin of a sponge boring results in a radial fabric of elongated to bladed calcite crystals. In rare examples, sponge borings are surrounded by subequant anhedral calcite. Where this unusual fabric occurs around a boring, it might be explained by the rapid advancement of a replacement front initiated along the margin of an adjacent boring.

Although neomorphic calcite is concentrated in portions of the shell that are intensely bored (Figure III-1), there is no apparent correlation between the degree of boring in the shell and the relative proportions of aragonite and calcite (Figure III-8).

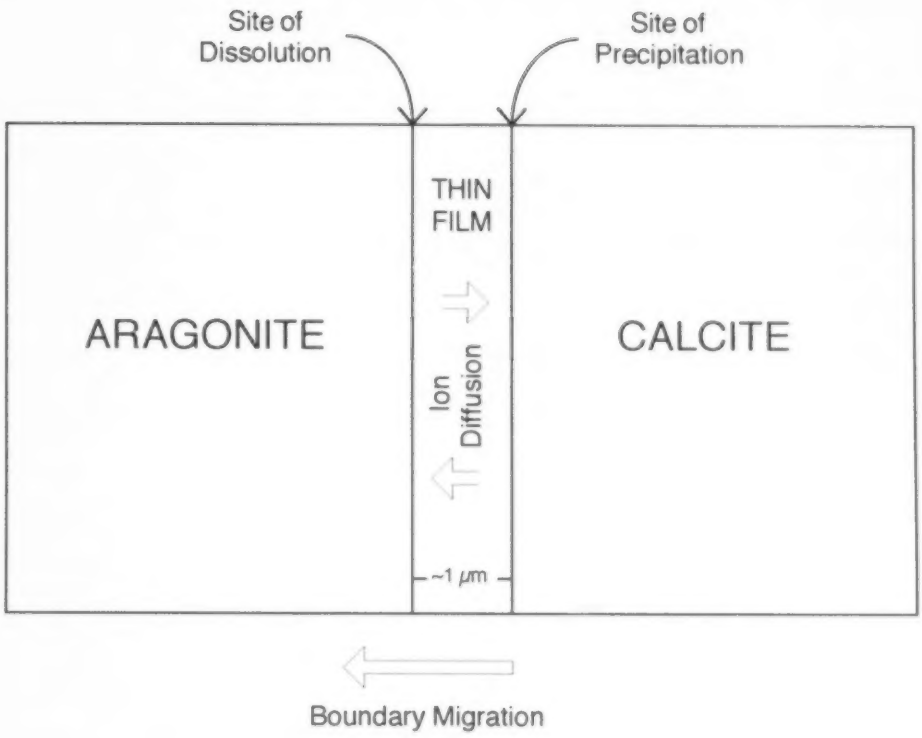


Figure III-7. Schematic diagram of *in situ* dissolution/reprecipitation across a thin solution film. Aragonite is dissolved on one side of the film and calcium and carbonate ions are diffused to the other side where calcite is precipitated. With continued dissolution and precipitation, aragonite is gradually replaced by calcite. Modified from Pingitore (1976).

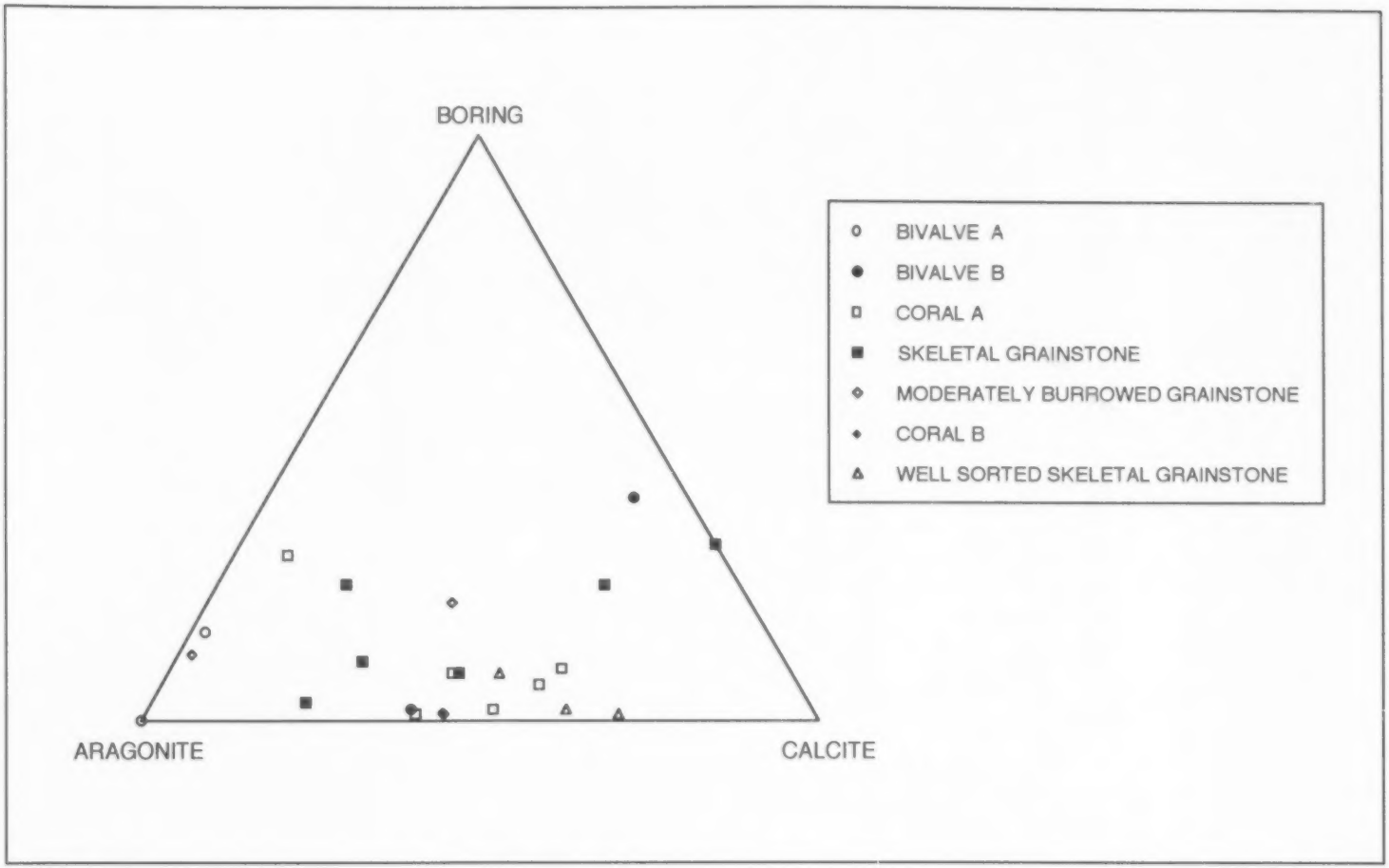


Figure III-8. Ternary diagram of percentage boring versus percentage aragonite and percentage calcite for samples of *Strombus gigas* from the Pleistocene Ironshore Formation.

The 'chalky transition zone' present between calcite and aragonite in partially replaced corals, as described by James (1974) and Pingitore (1976), is not evident in any of the *Strombus gigas* shells from Grand Cayman (this study) or Belize (Tebbutt 1967, 1975; Wardlaw *et al.* 1978). The presence of alteration halos around the sponge borings in aragonite, does suggest, however, that some alteration of the aragonite may precede inversion of aragonite to calcite.

Relict aragonite inclusions in neomorphically replaced Pleistocene fossils have been previously documented. Sandberg *et al.* (1973) described aragonite ultrastructural relics from corals, gastropods and bivalves from the Pleistocene Key Largo and Miami limestones. Similarly, Sandberg (1975) reported that aragonitic layers in the bimineralic bryozoan *Schizoporella floridana* from the Miami Limestone have been replaced by coarse neomorphic calcite that contains numerous relict skeletal aragonite crystals as solid inclusions that are in their original orientation. Aragonite relics are also reported from Jurassic bivalves (Sandberg and Hudson 1983).

Aragonite relics might be regarded as temporary components of the calcite mosaic, that will, given sufficient time, invert to calcite. Sandberg and Hudson (1983), however, reported that they are also present in the Jurassic bivalve *Neomiodon* . Sandberg and Hudson (1983) argued that aragonite inclusions are not necessarily a temporary feature, and suggested that aragonite relics are preserved because they were protected by organic sheaths that surround individual crystals. Further, they suggested that this protective coating was supplemented "...by excess organic matter released by dissolution of intervening crystals." (p. 886). They reported that the concentration of aragonite inclusions is highest in areas of greater organic concentration, and noted that despite their higher solubilities, aragonite relics are not preferentially removed during etching. Additionally, organic rich layers between subunits of crossed-lamellar structure commonly act as boundaries to the neomorphic calcite crystal mosaic. The preservation or dissolution of

aragonite crystals can be attributed to differences in the thickness or integrity of the protective organic coating.

Long term retention of aragonite inclusions is encouraged because the crystals of neomorphic calcite that surround relics are much larger and therefore isolate the aragonite from diagenetic fluids. These crystals are effectively protected from alteration unless there is complete remobilization of the stable calcite phase.

Sandberg *et al.* (1973) proposed that the presence or absence of aragonite relics was an indicator of phreatic or vadose diagenesis, respectively. After further study, Sandberg and Hudson (1983) revised this interpretation and argued that "...the nature of the intraskeletal alteration front is of greater importance in determining alteration texture and relic preservation than is the general diagenetic environment." (p. 887).

Controls on Diagenesis

The inter-relationships between degree of boring, type and amount of cement, degree of aragonite to calcite neomorphism, and depositional facies are complex, but can be summarized as follows:

1. the degree of boring is variable in all facies, but lowest in the reef tract and reef channel,
2. needle fibre calcite and micrite cements show no apparent correlation to facies, however, blocky calcite spar and pelsparite cements are most abundant in shells from the patch reefs and the reef tract,
3. blocky calcite spar cement is more abundant in shells that have undergone complete or near complete alteration to calcite,
4. the intensity of replacement by calcite shows no significant correlation to depositional facies, and
5. although sponge borings are important in influencing the texture of neomorphic calcite, there is no correlation between degree of boring and intensity of aragonite to calcite alteration.

IV. DIAGENETIC ALTERATION OF *SIDERASTREA SIDEREA* AND *MONTASTREA ANNULARIS*

Pleistocene *Siderastrea siderea* and *Montastrea annularis* have been modified by (i) precipitation of syntaxial aragonite needle cements, (ii) bioerosion, (iii) accumulation of sediments and cements in intraskeletal pores and borings, (iv) selective dissolution of the skeleton, (v) partial or complete alteration of the aragonite skeleton to calcite, and (vi) precipitation of blocky calcite spar and needle fibre calcite cement.

A. DIAGENETIC ALTERATION

Samples of *Siderastrea siderea* and *Montastrea annularis* from the Pleistocene of Grand Cayman display a wide range of stages and types of alteration. Some corals are entirely aragonite, some are partially dissolved, some are partly altered to calcite, whereas others are entirely calcite. The following discussion concentrates on those corals which have undergone partial alteration to calcite because these samples provide details of the nature of the process by which aragonite to calcite alteration has occurred.

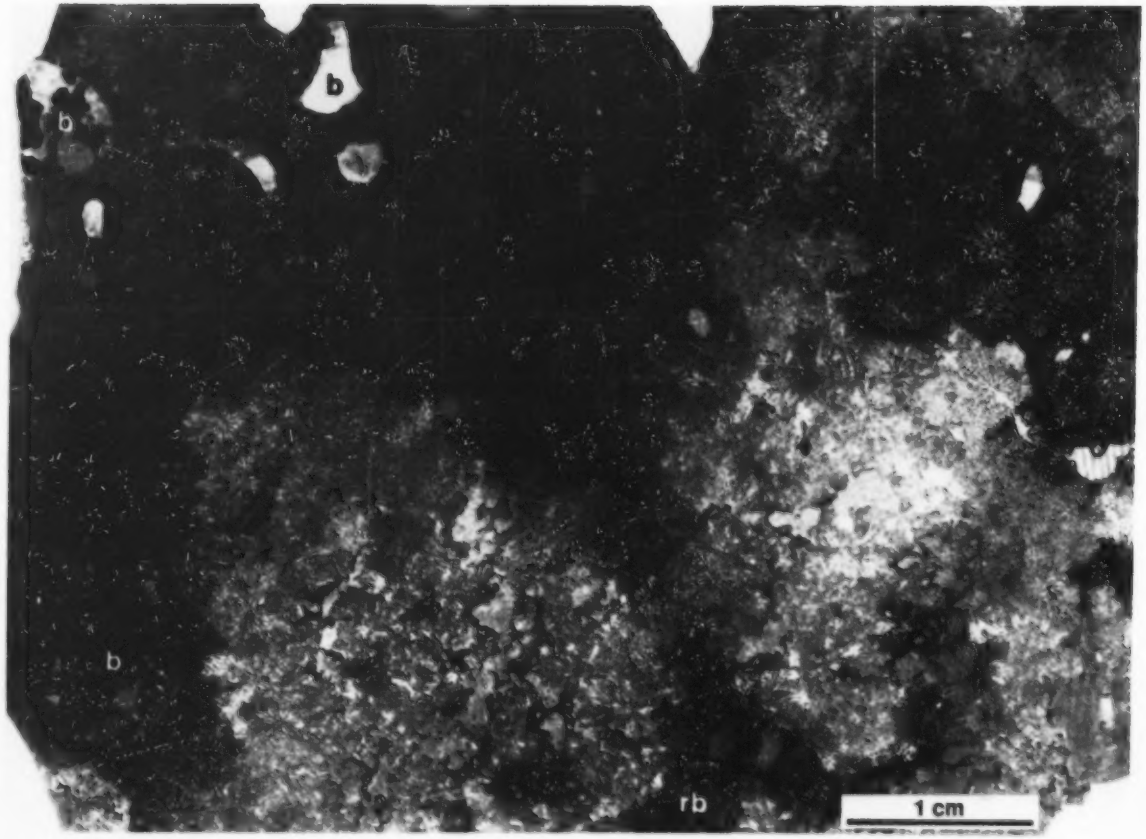
Siderastrea siderea

The mineralogical alteration of aragonite to calcite in *Siderastrea siderea* proceeds through a series of intermediate diagenetic stages that are evident in partly altered samples. The sequence of transitional textures that occurs between unaltered and altered portions of the coral is evident along septal columns in longitudinal and oblique sections, and between calices in transverse cuts through corallites. The transitional sequence can be divided into five zones based on textural and mineralogical criteria.

Thin section #3302 (locality CYC), prepared from a transverse cut through *Siderastrea siderea* (Plate IV-1), contains the entire spectrum of progressive diagenetic

Plate IV-1

Photograph of a thin section of *Siderastrea siderea* (B = boring, RB = root boring). The degree of alteration ranges from unaltered skeleton with syntaxial aragonite needle cement (Zone I - upper left) to calcite replaced and cemented (Zone V - lower center and lower right). See Figure IV-1 for the location of diagenetic zones (#3302, Loc. CYC).


b
b
b
rb
1 cm

zones (Figure IV-1). These zones are characterized and differentiated on the basis of mineralogical and textural criteria (Table IV-1).

Zone I

In Zone I, the trabecular structure of *Siderastrea siderea* is evident, with axes of septa and synapticulae defined by dark brown centers of calcification (Plate IV-2A).

Needle-shaped crystals of aragonite are present as syntaxial extensions of the aragonite fibres forming the trabeculae (Plate IV-2A). These syntaxial crystals are typically wider than the primary crystals on which they have formed (1 to 4 μm wide compared to 1 to 2 μm wide), have pointed terminations, and variable length (maximum of 150 μm) that is partly controlled by the size of the pore. In thin section, primary aragonite needles appear cloudy to brownish in color; whereas, the syntaxial overgrowths are clear. There is strong optical and structural continuity between the primary crystals and their owergrowths.

Crystal overgrowths from adjacent septa are commonly intermingled, but they do not join, and do not occlude the pore. The crystals forming the fibrous syntaxial fringe are loosely packed when compared with the tightly packed aragonite fibres in the trabecula. Considerable skeletal porosity is retained despite the addition of the cement.

Zone II

Alteration in Zone II is typified by selective dissolution of primary skeletal aragonite and syntaxial aragonite cement crystals.

Dissolution of syntaxial aragonite needle cement is most pronounced in the centers of calices, particularly along the columella and inner ends of the septa. Where substantial dissolution of cement is evident, the trabecular edge is commonly marked by a dark zone 5 to 8 μm wide. Remnants of the aragonite needle cement may or may not be preserved on the poreward side of this coating.

Figure IV-1. Diagenetic zones of *Siderastrea siderea*. B= boring, RB= root boring. Thin section #3302, Loc. CYC. See Table IV-1 for a summary of the textural characteristics of each zone.

ZONE I	Coral skeleton aragonite Trabecular structure evident Aragonite needle cement present as syntaxial extentions aragonite fibres forming the trabeculae
ZONE II	Coral skeleton aragonite Selective dissolution of primary aragonite along centers of calcification Partial or total dissolution of syntaxial aragonite needle cement
ZONE III	Transitional zone between aragonite and calcite skeleton Micrite coatings on intraskeletal pores well developed Elongate crystals of calcite cement extend along centers of septa Fingers of calcite from adjacent septa join through centers of the synapticulae to form irregularly shaped cystals
ZONE IV	Coral skeleton calcite Micrite coatings on intraskeletal pores well developed Coral skeleton consists of an interlocking mosaic of coarse-grained, irregularly shaped crystals of calcite
ZONE V	Coral skeleton consists of an interlocking mosaic of coarse-grained, irregularly shaped crystals of calcite Partial or total occlusion of intraskeletal cavities and borings by blocky calcite spar Needle fibre calcite cement in root borings

Table IV-1. Summary of the textural characteristics of diagenetic zones in *Siderastrea siderea*.

Plate IV-2

Diagenetic alteration of *Siderastrea siderea*.

(A) Thin section photomicrograph of Zone I. The trabecular structure of the unaltered aragonitic skeleton is evident. Dark centers of calcification (cc) are present along the middle of trabeculae. Aragonite needle cement is present as syntaxial extensions of the aragonite fibres forming the trabeculae (#3302, Loc. CYC).

(B) SEM photomicrograph of leached centers of calcification in Zone II (#3302, Loc. CYC).

(C) SEM photomicrograph of Zone II. Centers of calcification and aragonite needle cement are leached (#3302, Loc. CYC).

(D) SEM photomicrograph of Zone III. The leached centers of calcification are occupied by subequant crystals of calcite. Calcite crystals from adjacent centers join to form thin fingers of calcite that are separated from the pore walls by a zone of aragonite (a) (#3302, Loc. CYC).

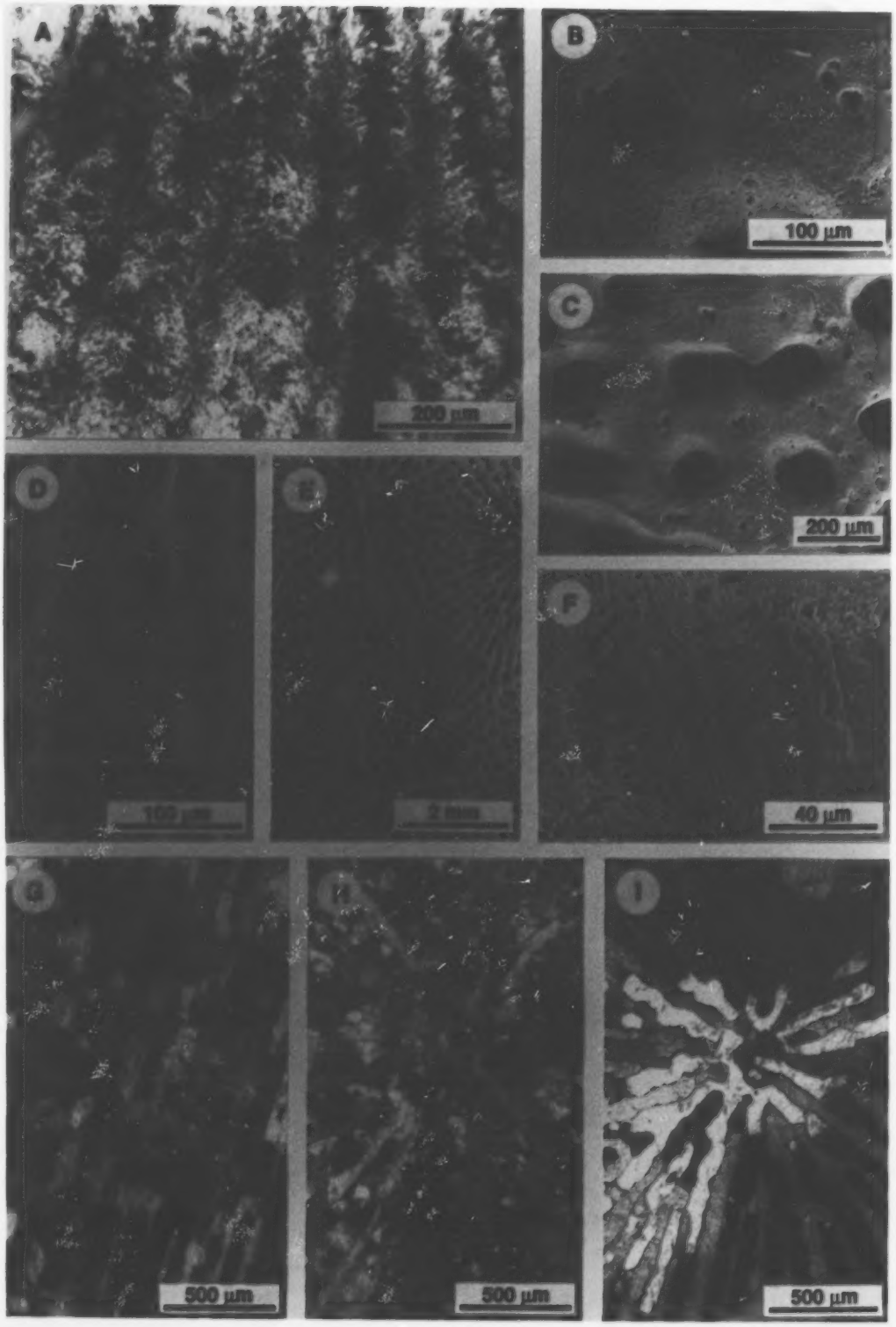
(E) SEM photomicrograph of Zone III. Irregularly shaped crystals of calcite are based along synapticulae and extend down the centers of septa towards the columella (#3302, Loc. CYC).

(F) SEM photomicrograph of the contact between aragonite (a) and calcite (c). The zone of aragonite immediately adjacent to the contact is porous and chalky. Aragonite needles in this zone are separated, etched, and ragged (#3302, Loc. CYC).

(G) Thin section photomicrograph of Zone IV. The coral skeleton consists of an interlocking mosaic of coarse-grained, irregularly shaped crystals of calcite (#2048, Loc. C).

(H) Thin section photomicrograph of Zone V. The coral skeleton is altered to calcite. Interskeletal pores are cemented by finely-crystalline calcite spar (#3302, Loc. CYC).

(I) Thin section photomicrograph of Zone V. The coral skeleton is altered to calcite. A single large crystal of calcite occupies the interconnected pores between septa and synapticulae (#3302, Loc. CYC).


A
200 µm
B
100 µm
C
200 µm
D
100 µm
E
2 mm
F
40 µm
G
500 µm
H
500 µm
I
500 µm

Primary skeletal aragonite is preferentially dissolved along centers of calcification which extend down the axes of trabeculae (Plate IV-2B). In transverse view, these dissolved centers are seen as equally spaced pores or voids along the length of the septa (Plate IV-2C). To a lesser extent, aragonite is also dissolved in the outer zones of the trabeculae, particularly leaching of the small equant crystals in the **brown zone**, and along the sides of the aragonite needles in the **peripheral zone**. Crystal boundaries of aragonite needles are ragged and uneven, and small pores are present between adjacent needles. There are no examples where solution has proceeded from the pore walls towards the centers of the trabeculae.

Overall, partial dissolution of primary skeletal aragonite serves to increase porosity substantially. This process of textural alteration is what James (1974), in his study of Pleistocene *Acropora palmata* from Barbados, referred to as **chalkification**. The chalky zone as described by James (1974) is a few μm to several cm thick and always occurs as a boundary between aragonite and calcite.

Zone III

Zone III is the transition zone between aragonite and calcite. As viewed under SEM, the leached centers of calcification along a transverse cut through a septa are occupied by irregularly shaped crystals of calcite that partly or completely occlude the voids (Plate IV-2D). Where the replacement process is more advanced, calcite crystals from adjacent centers join to form thin fingers of calcite which extend down the centers of the septa (Plate IV-2E). Along the leading edge of calcite replacement, these fingers are separated from the pore walls by zones of aragonite that become progressively thinner with increasing degree of alteration. Aragonite crystals in the zone immediately adjacent to the contact with calcite are commonly leached (Plate IV-2F). The extent to which this pore space is developed is variable. The zone of partly dissolved chalky aragonite is generally less than 50 μm wide.

Fingers of calcite from adjacent septa are joined through centers of the synapticulae to form irregularly-shaped crystals up to 5 mm wide. These crystals tend to straddle the synapticulothecae such that a single crystal of calcite has fingers which extend into two or more adjacent calices (Plate IV-2E). An individual crystal of calcite occupies up to 50% of the septa in a given calice. Micrite coatings line intraskeletal pores.

Zone IV

The coral skeleton in Zone IV has been altered to an interlocking mosaic of coarse-grained, irregularly shaped calcite crystals (Plate IV-2G). Relict trabecular structure is not evident. Areas between septa and synapticulae may be empty or lined with altered or pristine acicular aragonite cement. Micritic coatings on the surfaces of intraskeletal pores are well developed.

Zone V

Zone V is characterized by complete or near complete alteration of the skeleton to calcite, and partial to total occlusion of intraskeletal cavities by non-fluorescent, blocky calcite spar.

Intraskeletal pores are commonly filled by finely-crystalline calcite spar, 20 to 40 μm wide and 40 to 80 μm long (Plate IV-2H). Cementation by this relatively fine-grained cement is most prominent in the centers of the calices, and is commonly associated with secondary porosity created by root borings and associated, irregularly-shaped dissolution voids. Alternatively, the interconnected pores between septa and synapticulae may be filled with large calcite crystals, 50 to 150 μm wide and 100 to 200 μm long (Plate IV-2I). Some of these cement crystals are optically continuous with those crystals that replace the skeleton, however this type of cementation is relatively rare when compared with fabric selective mosaics. Micrite coatings on skeletal walls are well developed, even where cement and crystals that replace the skeleton are optically continuous. Where this occurs,

the micrite coating separates that part of the crystal that fills an original intraskeletal void, and that which has replaced the skeleton.

Montastrea annularis

In *Montastrea annularis*, the processes of mineralogical alteration of the skeleton and calcite cementation are strongly controlled by skeletal structure. The distribution of calcite and aragonite is influenced by seasonal differences in density, and differences in porosity and permeability between corallites and coenosteal areas.

The corallites are more porous and permeable than coenosteal areas, thus they act as fluid pathways through the coral. Superimposed on these vertical permeability pathways are horizontal differences in skeletal density between seasonal growth layers. Coral growth or skeletogenesis occurs by progressive addition of concentric layers of aragonite to the outer edge of the skeleton (Barnes 1970), and is strongly influenced by variations in light and water temperature (Baker and Weber 1975). In *Montastrea annularis*, annual growth consists of a thin, dense layer and a thicker, less dense layer. Although seasonal density banding in hermatypic corals is well known (Knutson *et al.* 1972; Buddemeier *et al.* 1974; Baker and Weber 1975; Buddemeier and Kinzie 1976), there is considerable controversy as to which of the alternating high or low density bands is associated with a particular season. Whereas Goreau (1977) reported that dense layers in *Montastrea annularis* from Jamaica formed in November and December, in *Montastrea annularis* from the Florida Keys, dense skeletal material was added in August and September (Hudson *et al.* 1976).

In *Montastrea annularis* from Grand Cayman, dense growth layers are 1 to 4 mm thick and the less dense layers are 3 to 5 mm thick. The combined thickness of these zones yields values that are well within the expected range for annual linear growth rates of *Montastrea annularis* provided by Gladfelter *et al.* (1978), and Hubbard and Scaturo (1985).

The occurrence of alternating vertical zones of high and low porosity and permeability (corallites vs. coenosteum), superimposed by horizontal differences in the density of growth layers, divides the coral into distinct areas that have undergone different types of diagenetic alteration (Plate IV-3). Four distinct diagenetic zones can be identified: Zone I - coenosteal areas of dense growth layers, Zone II - corallites of dense growth layers, Zone III - coenosteal areas of less dense growth layers, and Zone IV - corallites of less dense growth layers (Figure IV-2).

The degree of alteration of the skeleton to calcite is considerably higher in less dense growth layers, than in adjacent, more dense growth layers (Table IV-2). The columella, septa and endothecal dissepiments are preferentially leached compared to thecae, costae and exothecal dissepiments. Where leaching of corallites is extensive, this results in rounded calices as seen in transverse view (Plate IV-4A).

Syntaxial aragonite needle cements present in Holocene *Montastrea annularis* are rarely preserved in Pleistocene samples. Presumably, the aragonite cement has undergone dissolution during selective leaching of the skeleton. Micrite coatings are well developed on the surfaces of all primary intraskeletal cavities.

Zone I

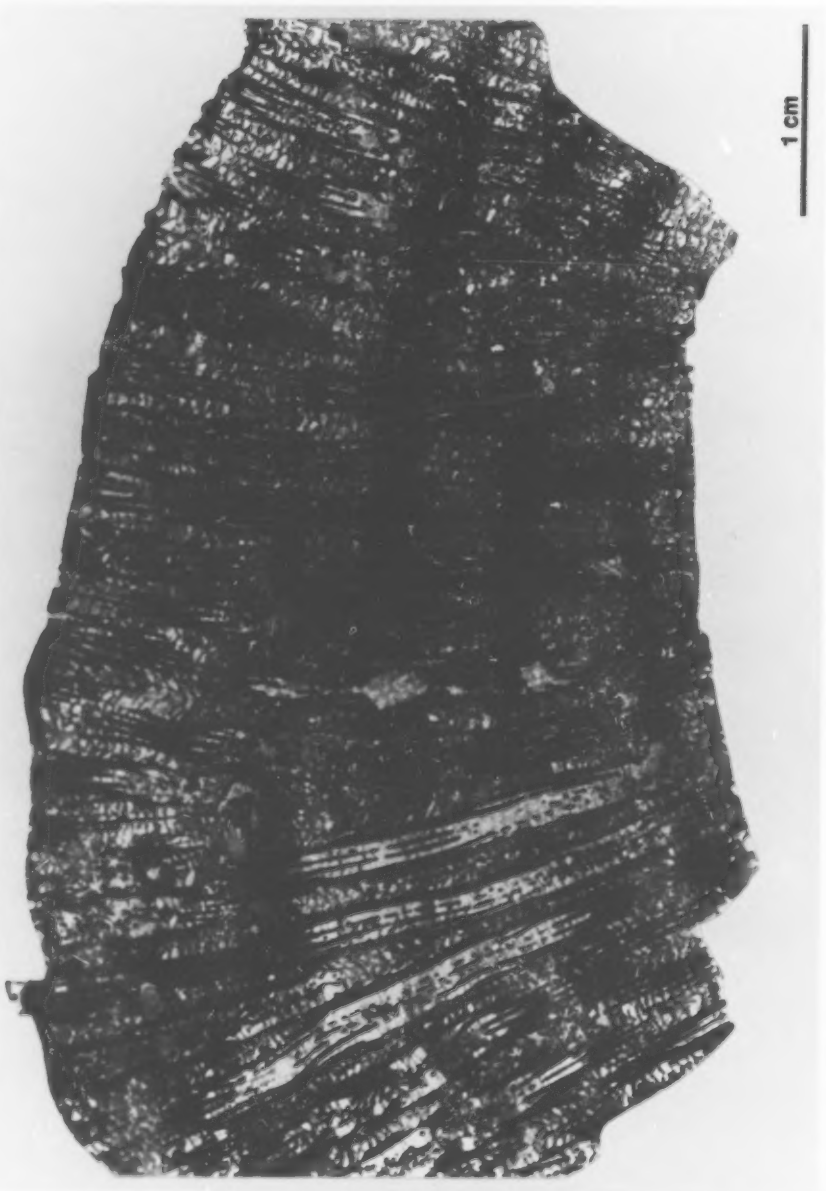
Coenosteal areas of dense growth layers, are characterized by minimal alteration of costae, thecae, and exothecal dissepiments to calcite (Plate IV-4B). The original trabecular structure of the coral is commonly still evident, and coenosteal pores contain no calcite cement.

Zone II

The septa, columella, and endothecal dissepiments of dense growth layers are extensively leached. Corallites are uncemented, and portions of the septa and the columella that remain are aragonite.

Plate IV-3

Photograph of a thin section of *Montastrea annularis*. Corallites (Zones II and IV) are preferentially leached compared to coenosteum (Zones I and III). Mineralogical alteration and cementation are most pronounced in less dense growth layers (Zones III and IV). See Figure IV-2 for the location of diagenetic zones (#2114, Loc. K).


1 cm

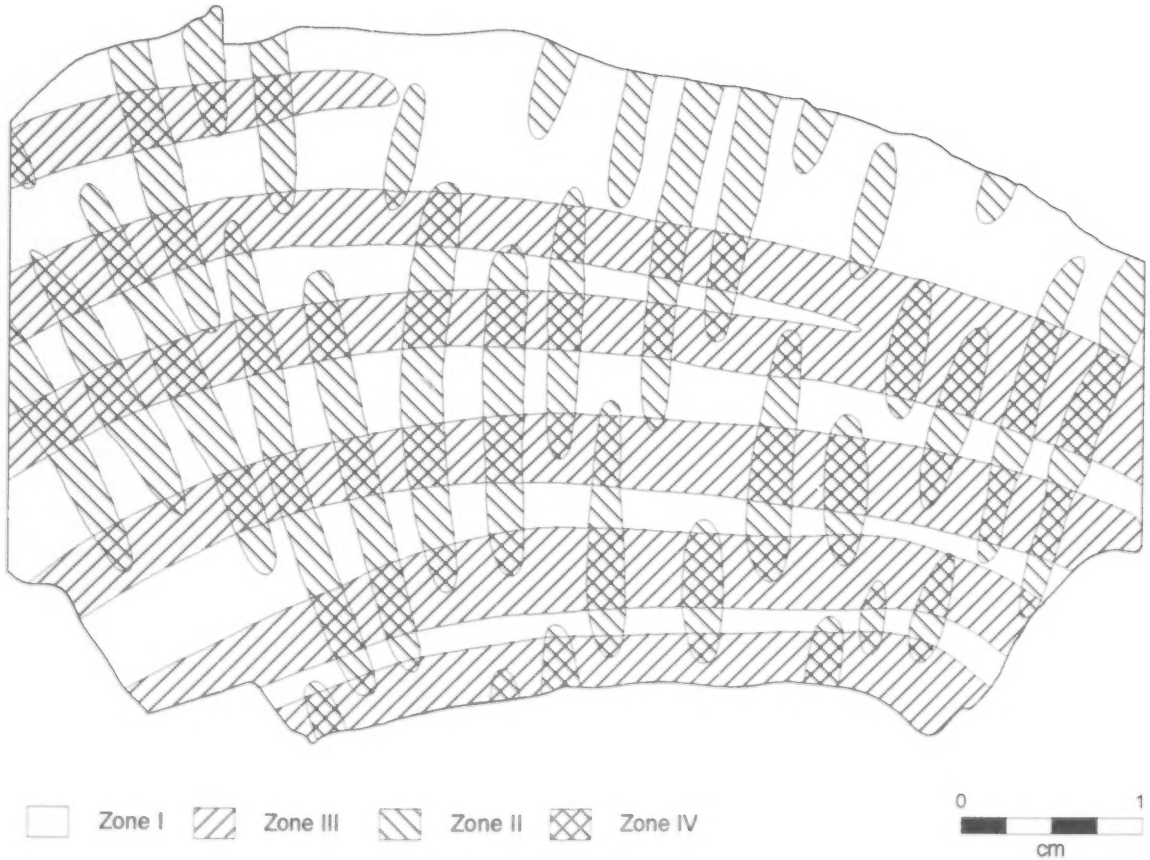


Figure IV-2. Summary of diagenetic zones in *Montastrea annularis*. Thin section #2114, Loc. K. See Table IV-2 for a summary of the textural characteristics of each zone.

	COENOSTEUM	CORALLITES
DENSE Growth Layer	**ZONE I** Coenosteal pores uncemented Minimal mineralogical alteration of costae, thecae and exothecal dissepiments Original trabecular structure of aragonite still evident	**ZONE II** Extensive dissolution of septa, columellae, and endothecal dissepiments Portions of septa and columella that remain are aragonite Corallites uncemented
LESS DENSE Growth Layer	**ZONE III** Coenosteal pores filled by coarse-grained calcite cement Costae, thecae, and exothecal dissepiments altered to fine-grained calcite Calcite crystals which replace the skeleton extend into coenosteal pores	**ZONE IV** Extensive dissolution of septa, columellae and endothecal dissepiments Portions of septa and columella that remain are aragonite or finely crystalline calcite Corallites usually uncemented but may be lined or filled by calcite cement

Table IV-2. Summary of the textural characteristics of diagenetic zones in *Montastrea annularis*.

Plate IV-4

Diagenetic alteration of *Montastrea annularis.*

(A) Photograph of a thin section through a less dense growth layer (Zones III and IV). The columellae and septa are extensively leached. Costae and thecae are altered to finely crystalline calcite, and coenosteal pores are cemented by calcite (#1987, Loc. C).

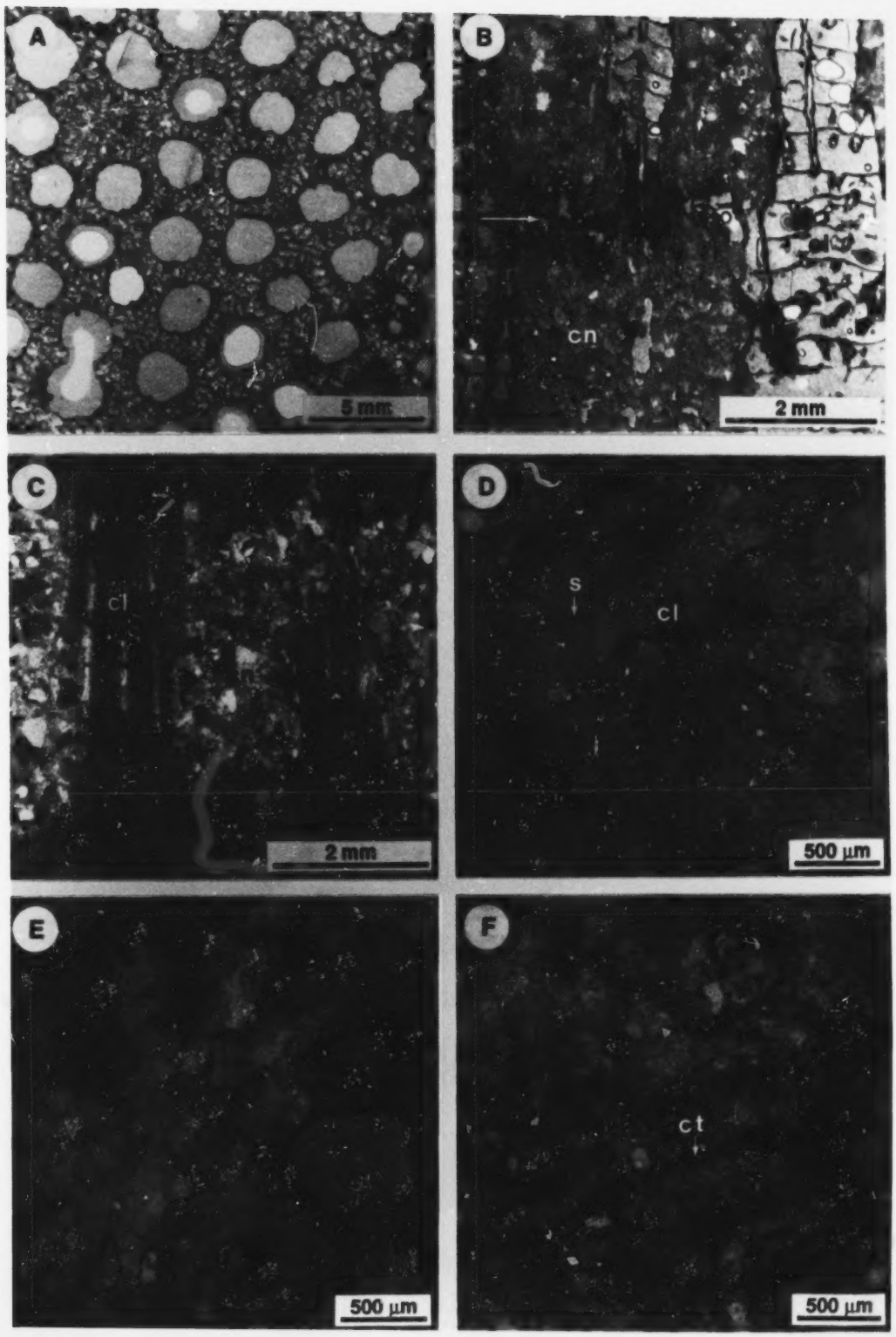
(B) Comparison of degree and type of alteration in different diagenetic zones. Coenosteal areas (cn) of less dense growth layers (Zone III) are altered to calcite and cemented. Minimal alteration and cementation occurs in the coenosteal areas (arrow) of more dense growth layers (Zone I). The corallites (cl) of the dense and less dense layers (Zones II and IV) are relatively unaltered and uncemented (#2727, Loc. ACB).

(C) Comparison of degree and type of alteration in different diagenetic zones. Coenosteal areas (cn) are preferentially cemented compared to the corallites (cl) (#2114, Loc. K).

(D) Thin section photomicrograph of Zone IV. Septa (s) are altered to finely-crystalline calcite and the corallite (cl) is cemented by calcite spar (#1987, Loc. C).

(E) Thin section photomicrograph of Zone IV. Calcite cement was precipitated in the corallite, and then the septa were leached, resulting in an internal mold of the calice (#1987, Loc. C).

(F) Thin section photomicrograph of Zone V. Costae (ct) are altered to finely-crystalline calcite, and coenosteal pores are cemented by coarse calcite spar (#1987, Loc. C).


A
5 mm
B
cn
2 mm
C
cl
2 mm
D
s
cl
500 µm
E
500 µm
F
ct
500 µm

Zone III

The coenosteal areas of less dense growth layers are characterized by extensive alteration of costae, thecae, and exothecal dissepiments to irregularly shaped, cloudy crystals of calcite 25 to 100 μm wide (Plate IV-4B; 4C; 4F). Coenosteal pores are thoroughly cemented by clear crystals of calcite spar 125 to 250 μm wide (Plate IV-4B; 4C and 4F), with rare crystals up to 500 μm wide. Calcite crystals that replace the skeleton commonly extend into coenosteal pores, resulting in a cross-cutting mosaic of calcite. Despite this, the original skeletal structure of the coral is preserved. Even where cement crystals and those replacing the skeleton are optically continuous, the surface of the intraskeletal cavity is marked by a zone of micrite averaging 20 μm in thickness. Crystals of cement can also be differentiated from those that replace the skeleton because they are clear rather than cloudy, and are typically coarser-grained. Although the external form of the coral is preserved in heavily cemented and calcitized areas, the original trabecular structure of the coral is not evident. Relict aragonite crystals were not observed, however the cloudy nature of crystals that replace the skeleton indicates the inclusion of organic remnants.

Zone IV

Remnants of septa and the columella in less dense growth layers may be either aragonite or calcite. Where septa are partly altered to calcite, the calcite occurs in the center of the septa and is surrounded on all sides by aragonite. The corallites of less dense layers are cemented (Plate IV-4D) or uncemented (Plate IV-4A). In some cases, cement has filled septal areas, and then the septa and columella have been leached, leaving an internal mold of the calice (Plate IV-4E).

Internal Sediments

Intraskeletal pores of *Montastrea annularis* and *Siderastrea siderea* are partly filled by loosely consolidated internal sediment. Due to the extremely porous nature of coral skeletons and the relatively low degree of cementation, most of this sediment has been removed during the preparation of thin sections. As a result, it is not readily available for detailed examination with the petrographic microscope. The sediment which remains is largely concentrated in borings in the skeleton.

The internal sediment in corallites of *Montastrea annularis* and *Siderastrea siderea* is composed of lime mud, lime sand, micrite, and microspar. All are original void fills or the alteration products thereof. The allochems include fecal pellets and peloids, 15 to 80 μm wide, and lesser amounts of skeletal fragments, 50 to 150 μm long. The micrite and microspar are closely associated and have a gradational contact, suggesting that the microspar is a product of aggradational recrystallization of original lime mud.

Internal sediments comprise a volumetrically insignificant proportion of these corals. Similarly, sedimentary detritus in *Acropora palmata* from Barbados comprises only 0 to 5% of the coral (Pingitore 1970).

Filling of the intraskeletal cavities with sediment postdated cementation by acicular aragonite, but predated blocky calcite spar, and probably occurred at the time of submarine burial of the skeleton following death of the coral.

Borings

Siderastrea siderea and *Montastrea annularis* have been extensively bored by *Lithophaga*, polychaete and sipunculid worms, sponges, algae, fungi and other bivalves. Jones and Pemberton (1988*a*, 1988*b*) provided a detailed description of *Lithophaga* borings and their fills in *Montastrea annularis* and *Diploria labyrinthiformis* from Pleistocene patch reefs of Grand Cayman. These borings are assigned to the ichnospecies

Gastrochaenolites torpedo as defined by Kelly and Bromley (1984), and many still contain the *Lithophaga* that was responsible for their generation.

Lithophaga produces clavate borings 4 to 14 cm long, and 0.3 to 4 cm in diameter. The borings are lined with fluorescent cryptocrystalline calcite, 0.1 to 0.5 cm thick, and contain cryptocrystalline calcite, porous cryptocrystalline calcite, honeycombed cryptocrystalline calcite, pelsparite, and pelmicrite (Jones and Pemberton 1988*b*). Jones and Pemberton (1988*b*) suggested that because of the distinctive fluorescent character of carbonate in the borings (indicates high organic content), *Lithophaga* probably played an active and important role in their formation.

Lithophaga borings occur as either closely spaced or widely spaced discrete entities, or may interpenetrate one another where multiple episodes of boring have occurred (Jones and Pemberton 1988*a*, 1988*b*). A complex array of sediments and cements results where one boring cross-cuts another. These borings are significant because they:

1. weaken the coral heads and make them more susceptible to physical breakdown (James 1970; Risk and MacGeachy 1978; Hadfield 1976),
2. liberate substantial quantities of $CaCO_3$ (James 1970; Jones and Pemberton 1988*a*, 1988*b*),
3. have dense calcareous linings which strengthen the substrate and make it less susceptible to weathering (Otter 1937; Jones and Pemberton 1988*a*, 1988*b*),
4. increase the surface area available for attack by bioeroders (Otter 1937; Jones and Pemberton 1988*a*, 1988*b*), and
5. provide sites for accumulation of sediment (Otter 1937; Kennedy and Klinger 1972; Marshall 1983) and precipitation of cement (Jones and Pemberton 1988*a*, 1988*b*).

Isopachous aragonite cements, which are common in the corallites, are absent from the borings. This suggests that either *Lithophaga* borings postdate aragonite cementation, or that the micro-environment of the borings is unsuitable for precipitation of aragonite (Jones and Pemberton 1988*b*).

Root Borings

Montastrea annularis and *Siderastrea siderea* contain irregularly shaped voids that were once the site of rootlets. The walls of the root borings are commonly lined with micrite and tangential needle fibre mats (Plate IV-5A). The needle fibre mats form coatings, up to 10 μm thick, that are comprised of calcite needles < 1 μm wide and up to 10 μm long (Plate IV-5B; 5C). Associated with these borings are dissolution cavities that have no surficial coatings on their walls. Both the root borings and the dissolution voids that are associated with them commonly contain randomly oriented needle fibre crystals, 1 to 2 μm wide and 10 to 50 μm long.

B. DISCUSSION

Aragonite Dissolution

Solution of the original aragonite skeleton of *Siderastrea siderea* is restricted to dissolution along the centers of trabeculae that accompanies aragonite to calcite alteration, and dissolution associated with root borings. In *Montastrea annularis*, these types of dissolution are important, but there is also substantial dissolution of the columella, septa, and endothecal dissepiments in the corallite. Minimal dissolution of septal areas occurs in *Siderastrea siderea.*

Differences in the types of dissolution between *Siderastrea siderea* and *Montastrea annularis* can be attributed to differences in skeletal structure. *Siderastrea siderea* is formed of cerioid colonies in which corallites share a common wall. There is no coenosteal area, thus porosity and permeability of the skeleton has a rather homogeneous distribution. In contrast, *Montastrea annularis* colonies are plocoid, and corallites are separated and united by coenosteum (costae and exothecal dissepiments). The more porous corallites act as fluid pathways and are therefore preferentially dissolved.

Plate IV-5

Root borings, needle fibre calcite and aragonite dissolution in *Montastrea annularis* and *Siderastrea siderea*.

(A) SEM photomicrograph of a root boring in *Siderastrea siderea*. The root boring is lined with micrite and tangential needle fibre mats, and contains randomly oriented lath shaped crystals of calcite (#3302, Loc. CYC).

(B) Detailed view of a tangential needle fibre mat on the wall of a root boring in *Siderastrea siderea* (#3302, Loc. CYC).

(C) SEM photomicrograph of calcite needles that form a needle fibre mat in *Siderastrea siderea* (#3302, Loc. CYC).

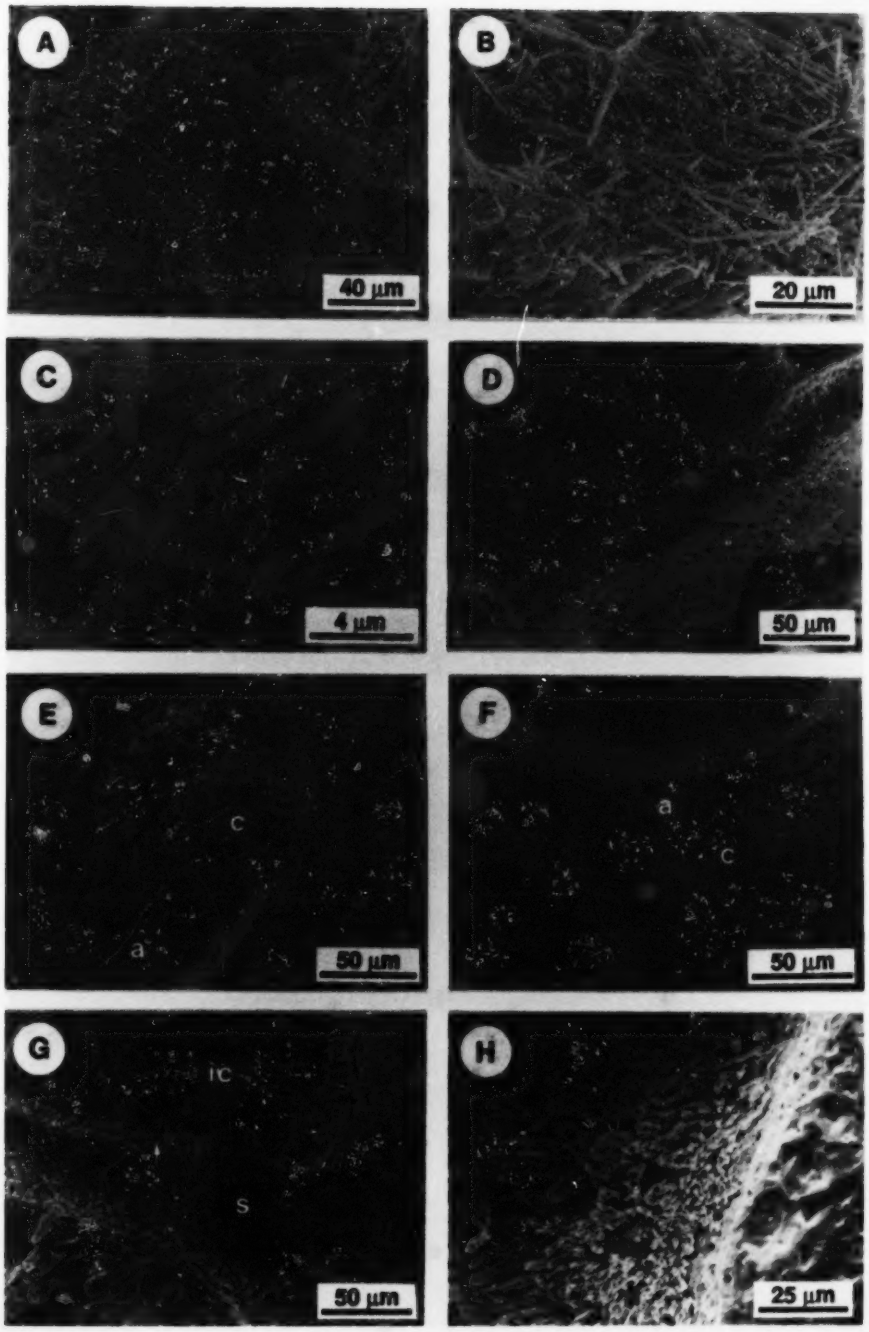
(D) SEM photomicrograph of preferential dissolution of the center of a trabeculae in *Montastrea annularis* (#2768, Loc. CYC).

(E) SEM photomicrograph of a calcite crystal (c) precipitated in a leached center of calcification along a chalkified aragonite (a) trabeculae in *Montastrea annularis* (#2768, Loc. CYC).

(F) SEM photomicrograph of chalky aragonite (a) at the contact with calcite (c) in *Montastrea annularis* (#2768, Loc. CYC).

(G) SEM photomicrograph of altered remnants of primary aragonite needle cement (arrow) along the surface between a septum (s) and a cemented intraskeletal pore (ic) in *Montastrea annularis* (#2114, Loc. K).

(H) Detailed view of the surface of an intraskeletal pore in *Siderastrea siderea* (#3302, Loc. CYC).


A
40 µm
B
20 µm
C
4 µm
D
50 µm
E
c
a
50 µm
F
a
c
50 µm
G
ic
s
50 µm
H
25 µm

Partly altered samples of *Siderastrea siderea* and *Montastrea annularis* contain intermediate diagenetic zones in which septa (and/or costae) are part aragonite and part calcite. In each case, dissolution and subsequent precipitation of calcite begins along the centers of the trabeculae (Plate IV-5D; 5E). Preferential leaching of the centers of calcification can be attributed to textural differences between the trabecular axis and surrounding zones. The axes of trabeculae are formed of small equant crystals of aragonite (Wainwright 1963, 1964). Intercrystalline spaces are filled with soluble organic material which undergoes rapid decay upon exposure of the skeleton (Spiro and Hansen 1970). This causes a significant increase in porosity along the centers of calcification, which allows percolating fluids to dissolve the small crystallites along the trabecular axis (James 1974).

As the leached channel of the trabecular axis is widened by continued dissolution, solution of the aragonite needles surrounding the axis begins (Plate IV-5F). Due to a faster rate of dissolution along crystal faces parallel to the c-axis (Fyfe and Bischoff 1965), aragonite needles are dissolved along their sides thereby causing separation of the crystals and creation of 'chalky' aragonite (James 1974).

The chalky aragonite described by James (1974) consists of a porous mass of separated, etched, and ragged aragonite needles. The needles are thinned and have been separated by solution along the crystal contacts. Chalky aragonite is present in all samples of *Acropora palmata* from Barbados, and varies from a few μm to several cm thick. In corals comprised of both aragonite and calcite, the two phases are always present as two distinct phases (and never as scattered domains), and are always separated by chalky aragonite. James (1974) reported that in thin section, 'chalky' aragonite is darker than the dense unaltered aragonite"...due to internal reflection of light in submicroscopic solution voids between aragonite needles" (p. 791). Zones of chalky aragonite observed by James (1974) in *Acropora palmata*, are not as well developed in samples of *Montastrea annularis* and *Siderastrea siderea* examined in this study. Chalkification is, however, more pronounced in *Montastrea annularis* than in *Siderastrea siderea.*

Whereas Pingitore (1970) suggested that solution proceeds inward from pore walls, the work of James (1972*a*, 1974), and this study, suggests that it begins along centers of calcification. James (1974) stated that "Solution of aragonite was never observed to have taken place from the pore walls inward..." (p. 790), but rather dissolution (and subsequent alteration to calcite) begins in the centers of *Acropora palmata* fronds. The presence of well developed micrite coatings on the surfaces of intraskeletal cavities act as a protective barrier which inhibits dissolution. In the case of *Montastrea annularis*, however, micrite coatings are not sufficient to prevent massive dissolution of septa, columellae, and endothecal dissepiments in the corallites of both dense and less dense growth layers.

Origin of Cements

Aragonite Needle Cement

Aragonite needle cements are indicative of the marine phreatic zone (James and Choquette 1983; Chafetz *et al.* 1988). The precipitation of these cements is generally regarded to be contemporaneous with active coral growth (Hubbard 1975; Macintyre 1977; Lighty 1985), with cementation occurring just below the surface of active skeletogenesis (Jones and Pemberton 1988*b*). Pingitore (1976) noted that the precipitation of aragonite needles is best developed in the reef crest, and concluded that "...physicochemical or biochemical processes of shallow agitated water are best suited for aragonite precipitation." (p. 988).

Pingitore (1970, 1976) described cement crusts (30 to 50 μm thick) on *Acropora palmata*, comprised of fine-grained equidimensional calcite crystals. These crusts occur alone, or as the outermost layer in a cement lined or filled void. They are interpreted to be the diagenetic alteration product of submarine aragonite needles. Aragonite needles are typically not preserved in calcitized skeletons except for rare cases where they are encased in crystals of void filling calcite cement. Pingitore (1976) suggested that this interpretation

is correct, based on the absence of these crusts from secondary dissolution voids created after removal from the submarine environment.

Aragonite needle cements are rarely preserved in calcitized samples or portions of *Siderastrea siderea* and *Montastrea annularis*. These cement crystals are either dissolved or altered during meteoric diagenesis. In *Siderastrea siderea*, micrite coatings are not well developed in portions of the coral that contain substantial amounts of aragonite needle cements (Zone I), but are pronounced in zones where acicular aragonite is absent. This suggests that micrite coatings represent, in part, the alteration product of syntaxial aragonite needle cement (Plate IV-5G; 5H).

Micrite Coatings

Micrite coatings on the walls of intraskeletal pores and borings are well developed in altered or partly altered zones of *Siderastrea siderea* and *Montastrea annularis*. These coatings have originated, in part, from the alteration of aragonite needle cements. In addition, it is likely that micrite was precipitated as a cement in the submarine (and vadose?) diagenetic environments. The sharp contact of the micrite with the skeleton precludes formation of the coatings by micritization associated with the activity of endolithic algae and fungi. Additionally, some of the micrite may be carbonate mud which has adhered to the sides of intraskeletal pore spaces in the subtidal environment. This interpretation was put forth by Sibley and Murray (1972) to explain the presence of fine-grained coatings in carbonate sediments from Bonaire.

Pelsparite

Pelsparite is dominantly confined to intraskeletal cavities near the exposed surfaces of the coral and in borings, and probably originates after active coral growth has ceased (Lighty 1985; Jones and Pemberton 1988*b*). This type of cement is interpreted as having formed in the submarine diagenetic environment by the inorganic and/or organically

induced precipitation of peloids and microspar directly from sea water (Macintyre 1977, 1985; Marshall 1983).

Blocky Calcite Spar

In *Siderastrea siderea* and *Montastrea annularis*, blocky calcite cement is concentrated in areas of the coral that have undergone alteration to calcite. In general, crystals of blocky calcite cement are not present in intraskeletal pores that lie immediately adjacent to the unaltered aragonitic skeleton. These factors suggest that calcitization of the coral skeleton precedes cementation of the pores by blocky calcite.

Pingitore (1970) suggested that the precipitation of calcite cement in intraskeletal pores of *Acropora palmata* from the Pleistocene of Barbados, was the direct result of excess carbonate (8% by volume) liberated by the mineralogical alteration of aragonite to calcite. He noted that small amounts of void-filling calcite are present in younger skeletons which have not yet equilibrated themselves with respect to fresh water (still aragonite), however the most calcite cement (nearly ten times more) occurs in mineralogically altered specimens, where it fills up to one-third of available macroporosity. Similarly, Pittman (1974) reported that corals which have been altered to calcite contain significant amounts of calcite spar cement whereas aragonitic corals contain very little. The concentration of void filling calcite in portions of the coral that have been altered to calcite led Pingitore (1970) to conclude that "...the precipitation of void fill is limited in time and space to the period and place of active skeletal inversion" (p. 720). Although he acknowledged that small amounts of calcite cement may be precipitated prior to alteration of the skeleton to calcite, he argues that the vast majority of calcite cementation occurs concomitantly with or later than aragonite to calcite alteration.

The absence of calcite cement in aragonitic skeletons can also be attributed, in part, to the difficulty of nucleating calcite cement on a substrate of aragonite. Pingitore (1970), however, rejected this explanation based on the observation that cementation in samples

from Barbados is not time continuous (i.e. older calcite samples contain the same amount of calcite cement as younger calcite samples). The percentage of calcite cement does not increase in older reefs, thus Pingitore (1970) argued that most of the cement must be derived from the 8% excess that is precipitated locally, and not from external sources.

The 8% (by volume) excess of carbonate liberated by the change from aragonite to calcite is due to a density difference between the orthorhombic and hexagonal crystallographic forms of the polymorphs (Pingitore 1970). Mass balance calculations indicate that 80% of the calcite cement in the calcite samples can be accounted for by this mechanism (Pingitore 1970).

Needle Fibre Calcite

Needle fibre calcite is dominantly confined to root borings and associated dissolution voids, indicating that they are precipitated in the near-surface diagenetic environment. Similar crystals were described from rhizoliths of Cayman Brac (Jones and Ng 1988), the Pleistocene of Barbados (James 1972*a*, 1972*b*; Steinen 1974; Harrison 1974, 1977), eolianites of Yucatan (Ward 1970, 1975), and subsurface calcarenites of Barbados (Supko 1971). The association of these crystals with surficial calcareous crusts and roots is well documented. The vadose origin of these crystals is substantiated by their occurrence in rocks which have only been exposed to vadose diagenesis (Steinen 1974). The decay of the organic matter in the roots may have promoted calcite precipitation, and influenced the morphology of the crystals.

C. DIAGENETIC MODEL

Diagenetic changes in *Siderastrea siderea* and *Montastrea annularis* occurred in both the submarine and meteoric environments (Figure IV-3). Submarine diagenesis of the corals involved:

1. precipitation of syntaxial aragonite needle cement,

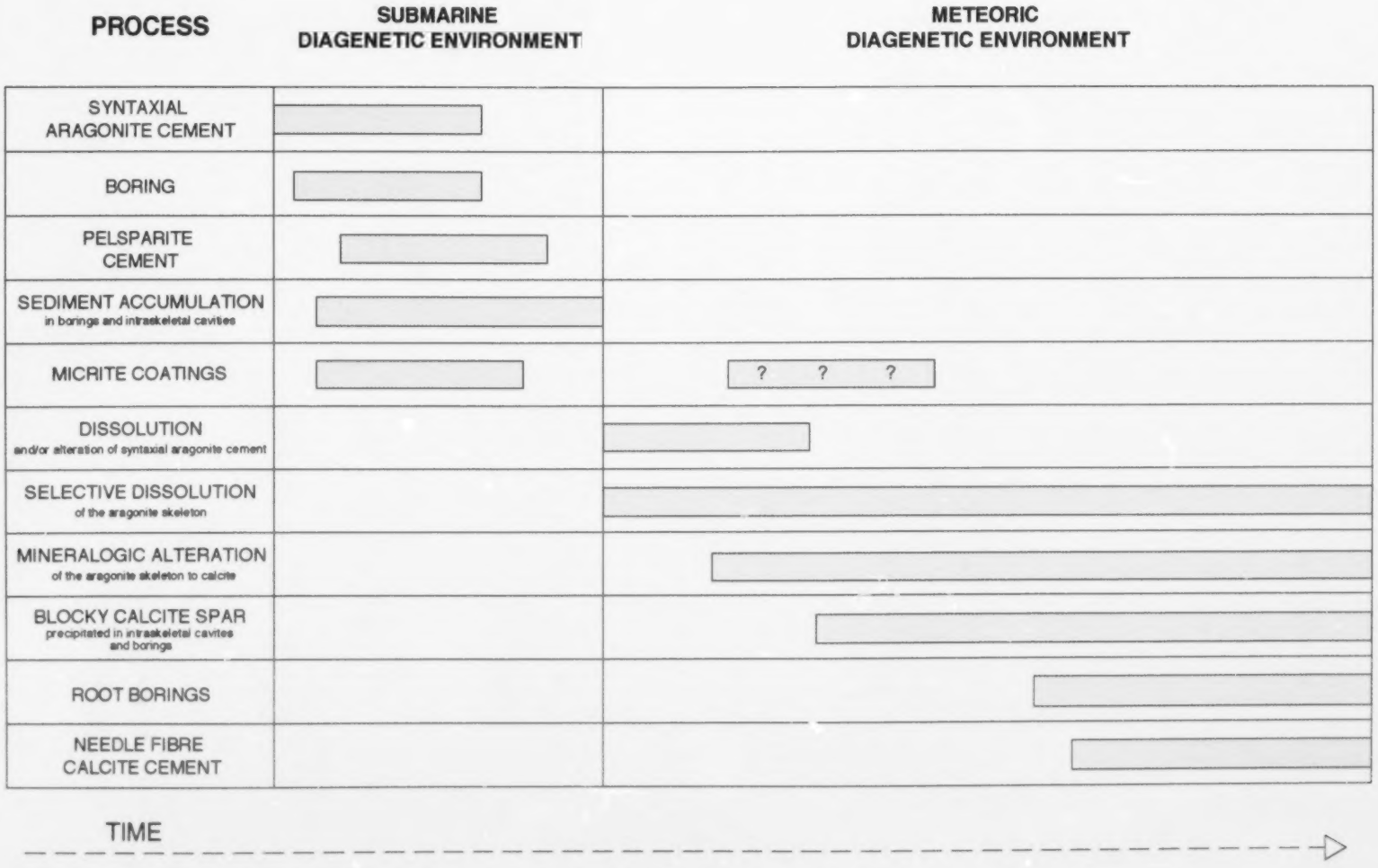


Figure IV-3. Summary of the diagenetic history of *Siderastrea siderea* and *Montastrea annularis*.

2. boring,
3. accumulation of sediment in borings and intraskeletal cavities, and
4. precipitation of micrite and pelsparite cements.

Diagenetic changes in the meteoric environment included:

1. dissolution and/or alteration of aragonite needle cement,
2. selective dissolution of the aragonitic skeleton,
3. partial or total mineralogical alteration of the skeleton to calcite,
4. precipitation of blocky calcite cement in intraskeletal cavities,
5. penetration by root systems, and
6. precipitation of needle fibre calcite.

Mineralogical Alteration

The mineralogic alteration of aragonitic skeletons of *Montastrea annularis* and *Siderastrea siderea* occurs by a combination of precipitation of calcite cement in voids created by progressive leaching of the skeleton, and thin film dissolution/reprecipitation.

In both cases, dissolution and subsequent precipitation of calcite begins along the trabecular axes of septa, synapticulae, costae, and thecae, and proceeds outwards to the walls of intraskeletal pores. No relict aragonite crystals were detected in the replacing calcite; however, the inclusion of organic matter is indicated by the cloudy nature of the crystals. The process of alteration of the skeleton to calcite is intimately associated with precipitation of calcite cement in intraskeletal pores.

Due to their extremely small size, the magnesium calcite and/or aragonite crystals comprising micrite coatings alter to low magnesium calcite extremely rapidly when exposed to meteoric waters. This alteration occurs much more rapidly than calcitization of the aragonitic skeletons that they encase (Friedman *et al.* 1971; James and Choquette 1984). Once altered to low magnesium calcite, these coatings are more resistant to dissolution than the aragonitic skeletal material, and act as protective barriers that prevent dissolution of the

skeleton from the pore walls inward. The presence of these resistant coatings has allowed the preservation of the original structure of the coral, even where obliterative, cross-cutting calcite mosaics are present.

Skeletal structure is important in controlling the aragonite to calcite alteration process. In partly altered *Siderastrea siderea*, the boundary between aragonite and calcite is commonly positioned along the axes of synapticulothecae. In transverse view, the surface of contact is seen as a polygonal outline which separates aragonite and calcite. Thin fingers of calcite extend ahead of the main front of replacement along the axes of trabeculae. In *Montastrea annularis*, replacement is strongly influenced by differences in porosity and permeability between corallites and coenosteum, and between dense and less dense growth layers. Septa, synapticulae, and endothecal dissepiments are preferentially dissolved compared to thecae, costae, and exothecal dissepiments, and mineralogical alteration is more advanced in less dense growth layers that in more dense growth layers.

Pingitore (1970) and James (1974) noted that younger corals from Barbados are composed almost exclusively of aragonite, whereas older samples have equilibrated to the subaerial environment, and are calcite. Whereas 83,000 year old corals are 10 to 30% calcite, 104,000 year old corals are 30 to 100% calcite (James 1974). This suggests that the replacement of aragonite by calcite is an ongoing (i.e. time continuous) process during meteoric diagenesis.

Porosity and Permeability Changes

Submarine and meteoric diagenesis of corals has substantially affected the porosity and permeability of *Siderastrea siderea* and *Montastrea annularis*. In the submarine environment, porosity was increased by boring by algae, fungi, worms, bivalves and sponges. Porosity decreased as a result of precipitation of syntaxial aragonite and micrite cements in corallites, and the accumulation of sand and clay-sized sediments and cements in corallites and borings. In the meteoric environment, the major factors that affected porosity

and permeability were alteration of the skeleton to calcite, calcite cementation and aragonite dissolution.

Calcite cementation is volumetrically the most important control on porosity. The precipitation of calcite cement in intraskeletal pores of *Siderastrea siderea* and *Montastrea annularis* has resulted in an overall decrease in porosity of the skeleton. Pittman (1974) noted a similar decrease in the porosity of Pleistocene corals of Barbados (9% decrease in *Montastrea annularis*), and also noted that permeability increased (> 1,000% in *Montastrea annularis*) due to changes in pore aperture size associated with fabric changes that accompanied recrystallization. Corals that have undergone alteration to calcite have larger and better sorted pore apertures than do their unaltered aragonitic counterparts (Pittman 1974). Preferential cementation in less dense growth layers, and preferential dissolution of corallites in *Montastrea annularis* from Grand Cayman has had a similar affect on permeability.

V. DISCUSSION

The instability of aragonite at normal temperatures and pressures (Jamieson 1953; Clark 1957; Fyfe and Bischoff 1965) leads to its replacement by calcite when subjected to the conditions of the meteoric environment. This mineralogic alteration has been extensively documented in Pleistocene carbonates of Florida and the Bahamas (Ginsburg 1957; Stehli and Hower 1961), Barbados (Matthews 1968; Steinen and Matthews 1973; James 1974; Pingitore 1970, 1976), and Bermuda (Friedman 1964; Land 1967).

The mineralogical change from aragonite to calcite involves a change from orthorhombic to hexagonal crystallographic form (James and Choquette 1984), and the liberation of 8% (by volume) excess calcium carbonate (Pingitore 1970). This excess carbonate may contribute significantly to calcite cement (Pingitore 1970).

Mineralogical transformation of aragonitic skeletal components to calcite in the meteoric diagenetic environment may occur by *in situ* neomorphic replacement of aragonite by calcite, or dissolution of aragonite and subsequent precipitation of calcite. Neomorphic replacement occurs by *in situ* dissolution/reprecipitation across a thin solution film in the absence of an appreciable void stage (Bathurst 1964; Friedman 1964; Folk 1965; Dodd 1966; Tebbutt 1967; Kinsman 1969; Folk and Asserto 1976; Pingitore 1976; Wardlaw *et al.* 1978). In contrast, the latter process involves the precipitation of cement in voids created by dissolution of aragonite. Although these two processes are commonly regarded as separate diagenetic processes, they may also be "...interpreted as end members of a continuum based on a single mechanism" (Carlson 1983, p. 211).

A. CONTROLS ON THE ALTERATION OF ARAGONITIC SKELETAL COMPONENTS TO CALCITE

Significant controls on the stabilization of aragonitic skeletal components to calcite include time, climate, facies, skeletal composition, structure and microstructure, and diagenetic environment.

Time

Ancient carbonate sequences in the geologic column are composed of stable mineralogy (calcite and dolomite), whereas Recent and Pleistocene carbonates contain significant amounts of unstable aragonite (Stehli and Hower 1961; Friedman 1964; Land 1967). Given time, these rocks will equilibrate themselves to meteoric conditions and will undergo change to stable mineralogy.

On the coral cap of Barbados, older terraces contain higher proportions of calcite and less aragonite that do younger terraces at lower elevations (Broecker *et al.* 1968). The youngest terrace (dated at 82,000 years) is dominantly composed of aragonite, whereas those terraces older than 500,000 years are composed entirely of calcite (Matthews 1968). Intermediate terraces contain both aragonite and calcite, and the proportion of calcite increases with age of the terrace. The island has undergone gradual tectonic uplift (0.3 m per 1,000 years - Mesolella *et al.* 1970) during the Pleistocene, thus the reef terraces have been subaerially exposed since shortly after their formation. This suggests that given continual exposure to meteoric fluids, complete alteration of Pleistocene carbonates to calcite occurs within 500,000 years.

James and Choquette (1984) suggested that stabilization of carbonate sediments of Bermuda probably requires 100,000 to 1,000,000 years. In contrast, the sediments of Joulters Cay may equilibrate within only 10,000 to 20,000 years (Halley and Harris 1979), possibly because of the high aragonite content of these oolitic deposits (James and Choquette 1984).

Corals from the upper part of the Pleistocene Ironshore Formation of Grand Cayman have been dated at 124,000 +/- 8000 years (Woodroffe *et al.* 1983). The degree of alteration of Pleistocene skeletons of *Strombus gigas*, *Siderastrea siderea* and *Montastrea annularis* to calcite is variable. Although some skeletons are composed of aragonite, most contain both aragonite and calcite and some are entirely calcite. This indicates that given the right conditions, equilibration of skeletal components can occur within a geologically short period of time.

Despite evidence of relatively rapid equilibration of unstable mineralogy, there are numerous examples of aragonite preserved in ancient sequences. In each case, conditions have existed that inhibited the passage of fluids necessary for dissolution and precipitation. For example, Bruni and Wenk (1985) reported that corals, gastropods and bivalves in the Triassic San Cassiano Formation of Italy retain aragonite because of extremely low porosity related to the presence of clay and early cementation processes. Additionally, Fyfe and Bischoff (1965) reported the occurrence of Paleozoic aragonite molluscs encased in impervious matrix.

Climate

Matthews (1968) demonstrated that the speed of the stabilization process is controlled in part by the amount of rainfall and evaporation. Pleistocene reef tracts in high-rainfall (1500-2000 mm/year), low-evaporation terrains of Barbados contain greater amounts of calcite relative to aragonite than reef tracts of comparable age that lie in relatively low-rainfall (1250 mm/year), high-evaporation areas (Matthews 1968; James 1974). Mineralogic stabilization proceeds at a much reduced rate under dry climatic conditions. Pleistocene rocks of Hogsty Reef, Bahamas, show excellent preservation of original mineralogy, due to the less than 800 mm of rain received per year (Pierson and Shinn 1985). Similarly, Ward (1973) attributed the retention of metastable mineralogy in Pleistocene eoliantes of Yucatan to a dry climate during early subaerial diagenesis.

Present day rainfall on Grand Cayman is irregularly distributed, and varies from year to year, however, most precipitation is received by the western and southwestern portions of the island (Ng 1990; Ng *et al.* in press). Average daily temperatures range from 25 to 30ºC, and rainfall between 1920 and 1987 averaged 1513 mm/year (Ng 1989, pers. comm.). Due to the presence of an extensive karst system, rain that falls to the surface does not collect in freshwater ponds or streams, but rather it is quickly channelled into the subsurface. Comparison of the degree of aragonite to calcite alteration of skeletal components from different parts of Grand Cayman indicates no significant geographic distribution of highly-altered and non-altered samples.

Facies

The grain size, porosity and permeability of depositional facies may be important in controlling diagenetic processes such as cementation and mineralogical alteration. For example, sedimentary facies dominated by very fine- and fine-grained particles alter more rapidly than do calcarenites or large fossils (Purdy 1968; Matthews 1968; James and Choquette 1984). Sediments characterized by high permeability may contain relatively higher proportions of cement because they permit the passage of large volumes of fluid (James and Choquette 1984).

On Grand Cayman, depositional facies exerts an important control on degree and type of cementation, and degree of alteration of fine-grained non-skeletal and skeletal components. The degree to which facies controls aragonite to calcite alteration in large skeletons of *Strombus gigas*, *Montastrea annularis* and *Siderastrea siderea* is negligible. Comparison of the number of unaltered and altered samples, and the proportion of calcite in partly altered specimens reveals that there is no significant correlation between degree of alteration and depositional facies.

Skeletal Composition, Structure and Microstructure

Recognition that some carbonate components are more susceptible to alteration than others has led to the documentation of susceptibility rankings for skeletal and non-skeletal carbonates (Schlanger 1964; Land 1967; Purdy 1968; Milliman 1974; Scoffin 1987). Although the rankings in different schemes may vary, it is clear that two of the most important considerations in diagenetic susceptibility are original mineralogy, and the size, orientation and habit of crystals (skeletal structure and microstructure). Additionally, Banner and Wood (1964) suggested that foreign ions such as magnesium, and organic components of the skeleton may also influence diagenetic susceptibility.

In the case of *Siderastrea siderea*, *Montastrea annularis* and *Strombus gigas*, the original skeletal mineralogy is aragonite. Differences in the manner in which aragonite is replaced by calcite are therefore controlled by differences in the original skeletal structure, including amount and distribution of porosity, and arrangement and size of aragonite crystals.

The crossed-lamellar structure of *Strombus gigas* is comprised of an extremely dense arrangement of parallel rod-shaped aragonite crystals. Porosity in this structure is extremely low, thus the only significant pore space within the shell is that created by boring. These borings are important in controlling the way in which replacement proceeds, and the diagenetic texture that results. In addition, growth lines and boundaries between shell layers are known to influence boundaries in replacement calcite mosaics (Land 1967; Bathurst 1964, 1975; Schroeder 1973; and this study). Sandberg (1975) suggested that this is probably due to higher organic content along these contacts.

In contrast, the scleractinian corals *Montastrea annularis* and *Siderastrea siderea* are comprised of a porous network of trabeculae that allows for relatively efficient circulation of meteoric fluids. Based on study of Recent and Pleistocene corals of Barbados, Constanz (1985) argued that variation in the diagenetic susceptibility of scleractinian corals is controlled by each taxon's non-mineralogic skeletal properties. All scleractinian corals

are aragonite, thus diagenetic susceptibility is controlled not by composition, but by the reactive surface area of the skeleton. Aragonite fibre diameter and degree of aragonite fibre packing were identified as the critical factors in determining each taxon's relative diagenetic susceptibility in the meteoric phreatic environment (Constanz 1985). In addition, branching corals are more susceptible to dissolution than massive colonies, and diagenetic susceptibility increases with increasing surface area to volume ratio (Pittman 1974).

Constanz (1985) demonstrated that coral species with the narrowest (< 0.05 μm) aragonite fibres (e.g. *Acropora*) or most loosely arranged crystals are more susceptible to subsequent meteoric diagenesis that are coral species with wider (1 - 4 μm) or more densely packed aragonite crystals (e.g. *Montastrea*, *Siderastrea*, and *Diploria*). The exponential increase in the solubility with decreasing crystal size below 1 μm has been confirmed by experimental data (Chave and Schmaltz 1966), and can be explained in terms of the large ratio of reactive surface area to particle size (James and Choquette 1984).

Differences in the susceptibility of skeletal aragonite to dissolution explain why the process of chalky alteration or chalkification as described by James (1974) is more pronounced in *Acropora* than in *Montastrea* and *Siderastrea*.

Martin *et al.* (1986) examined neomorphically replaced *Montastrea annularis* and *Strombus gigas* from the Key Largo Limestone of Florida and concluded that "Skeletal porosity influences both the morphology of the neomorphic front and the composition of diagenetic calcite..." (p. 201). The neomorphic front in *Montastrea annularis* is highly irregular and not controlled by skeletal microstructure, whereas in *Strombus gigas* it is either irregular, or aligned with growth bands in the shell. Trace element and isotopic chemistry of neomorphic crystals indicates that in *Montastrea annularis*, there has been significant exchange between formation waters and water at the neomorphic front. In contrast, the chemical composition of neomorphic calcite in *Strombus gigas* is similar to that of the original aragonite, indicating that fluid exchange has been more limited (Martin *et al.* 1986).

Skeletal porosity also controls the rate of migration of the diagenetic front, as higher porosity and available surface area contribute to increased rates of aragonite dissolution and calcite precipitation (Martin *et al.* 1986). Based on differences in the thickness of altered rims of *Montastrea annularis* (4 cm) and *Strombus gigas* (0.5 cm), Martin *et al.* (1986) calculated that neomorphism was six times faster (by volume) in porous skeletons of *Montastrea annularis* than in dense shells of *Strombus gigas.*

Diagenetic Environment

The submarine, vadose, and freshwater phreatic diagenetic environments are characterized (and distinguished) by significant differences in hydrological, chemical, and biochemical parameters. Although significant variations can and do occur in a given diagenetic realm (e.g. water chemistry, temperature and saturation), certain diagenetic processes are specific to one or more diagenetic realm.

Aragonite dissolution, calcite cementation, and aragonite to calcite neomorphism are known to occur in the vadose and the freshwater phreatic environments. It is widely accepted, however, that diagenetic processes are more rapid in the freshwater phreatic diagenetic environment than under vadose conditions (Ginsburg 1957; Schlanger 1963; Land 1970; Harris 1971; Steinen and Matthews 1973; Matthews 1974; Pingitore 1976).

Most carbonate rock sequences have undergone diagenesis in more than one diagenetic environment, thus it is desirable to use mineralogical, chemical and textural criteria to identify the diagenetic realms that have affected the rocks, and to map out the diagenetic pathway or history of movement of the rocks through the different diagenetic realms. In terms of the alteration of aragonitic skeletal components to calcite, many attempts have been made at establishing links between various diagenetic textures, the process responsible for these textures, and the diagenetic environment within which the process operates. Despite recent advances in the interpretation of diagenetic textures, considerable confusion still remains.

Pingitore (1976) coined the term **cross-cutting mosaic** for calcite mosaics in which individual calcite crystals extend out from the coral skeleton into the void filling cement. He suggested that this texture is indicative of phreatic alteration, and noted that these corals contain more calcite cement and secondary porosity than their vadose counterparts. Phreatic transformation takes place across an intermediate chalky zone that represents a region of extensive, although mostly temporary, development of secondary porosity. Pingitore (1976) suggested that phreatic mosaics are composed of large, generally equant crystals, which are commonly up to several mm across. In contrast, vadose-altered corals are characterized by **fabric selective mosaics**, in which boundaries of filled primary voids serve as crystal boundaries in the calcite mosaic, and crystal size rarely exceeds 100 μm (Pingitore 1976). Aragonite to calcite transformation takes place by thin film transformation across a 1 μm (or less) film of water.

Although the use of fabric-selective mosaics and cross-cutting mosaics as criteria for distinguishing between *in situ* neomorphic transformation (inferred to occur under vadose conditions) and aragonite to calcite alteration via chalkification (phreatic alteration) has some application, an examination of the textures of skeletal components from various known diagenetic environments suggests that this may be an oversimplification of a complex situation. James (1974), for example, provided a detailed description of the vadose chalkification of *Acropora palmata*. In addition, Land (1970) described neomorphically replaced skeletons from the phreatic zone of Bermuda, and Schroeder (1973) reported that neomorphic crystals of vadose-altered vermetid gastropods are in optical continuity with cement (i.e cross-cutting mosaic). These examples suggest that the controls on the mechanism of aragonite to calcite alteration are not limited to differences between the vadose and phreatic diagenetic environments, but also include variations in hydrologic and chemical parameters that occur within diagenetic environments. Petrographically, fabric-selective and cross-cutting mosaics are not necessarily mutually

exclusive, as shown by Sandberg and Hudson (1983), who observed both textures in the Jurassic bivalve *Neomiodon.*

An alternative approach is to relate different types of diagenetic processes and products to water chemistry and kinetics of vadose water percolation. Harris and Matthews (1968), and Matthews (1968) argued that undersaturated fluids, passing rapidly through the sediment will tend to dissolve aragonitic skeletons and transport calcium carbonate to the water table. The cavities in the skeleton that are created by this dissolution, if preserved, may be filled with calcite cement at a later time. If, however, the movement of water is sufficiently slow, and the surrounding fluids remain saturated or super-saturated with respect to calcite, solution of aragonite and precipitation of calcite may occur concurrently and the skeleton will be altered to calcite without the formation of discernible void space.

B. SEA LEVEL HISTORY AND DIAGENESIS

Similarity between the diagenetic history of comparable carbonate deposits on different Caribbean Islands has led to the suggestion that diagenetic development may be related to regional events (Sibley 1980; Jones *et al.* 1984). Changes in sea level significantly affect the hydrologic regimes of both islands and Caribbean coastlines, and thus have profound effects on the movement of carbonate rocks and sediments through different diagenetic environments (James and Choquette 1984). The effects of these sea level changes differ slightly for deposits on tectonically active islands (e.g. Barbados - controlled by both tectonic and eustatic changes) compared to those of relatively stable carbonate areas (e.g. Bahamas, Bermuda, Cayman Islands, Yucatan - controlled mainly by eustatic changes).

Pleistocene glacio-eustatic sea level events have been documented from geological and geochronological data from Barbados (Broecker *et al.* 1968; Matthews 1973; Steinen *et al.* 1973; Stearn 1976), Bermuda (Land *et al.* 1967; Harmon *et al.* 1978, 1981; Vacher and

Hearty 1989), the Bahamas (Neumann and Moore 1975; Carew *et al.* 1984; Carew and Mylroie 1986; Stowers *et al.* 1988; Chen *et al.* 1991), Jamaica (Digerfeldt and Hendry 1987), and New Guinea (Aharon 1983). These data demonstrate that numerous significant changes in sea level have occurred since the Late Pleistocene. Although sea level curves constructed from different data commonly differ in the exact position of the sea during any given time interval, there is relatively good agreement that relative sea level highstands occurred around 125,000, 105,000, 82,000, 60,000 and 40,000 years B.P. (Figure V-1).

On the Cayman Islands, a number of coastal and shallow marine features confirm that Pleistocene sea level changes have influenced carbonate deposition, erosion and diagenesis. These include (summarized after Ng *et al.* in press):

1. wave cut notches at +6 m along the north coast of Grand Cayman (Jones and Hunter 1990), and around Cayman Brac (Woodroffe *et al.* 1983; Jones and Hunter 1990) that are interpreted to have formed at the time of deposition of the Ironshore Formation 125,000 years ago (Jones and Hunter 1990),
2. submerged wave cut notches at -19 m and -150? m around Grand Cayman (reported by pilots of the research submersible submarine), and
3. marine terraces at +2 m, +4 m, +6 m, +8 m, +11 m, and +15 m (Emery 1981), and submerged terraces at -5 to -10 m and -20 m (Rigby and Roberts 1976).

Comparison of the present day elevation of these features on Grand Cayman, Cayman Brac and Little Cayman allowed Jones and Hunter (1990) to conclude that the three islands have not undergone independent vertical movement during the last 125,000 years.

The coral cap of Barbados is an excellent location for study of Pleistocene sea level fluctuations because numerous reef terraces have been created by the interaction of relatively constant tectonic uplift and Pleistocene sea level fluctuation (Broecker *et al.* 1968; Mesolella *et al.* 1969, 1970). Mineralogical evidence from a cored borehole (#17) in a 105,000 year old reef tract (Steinen and Matthews 1973) documents the transition of Pleistocene rocks through different diagenetic environments in response to sea level

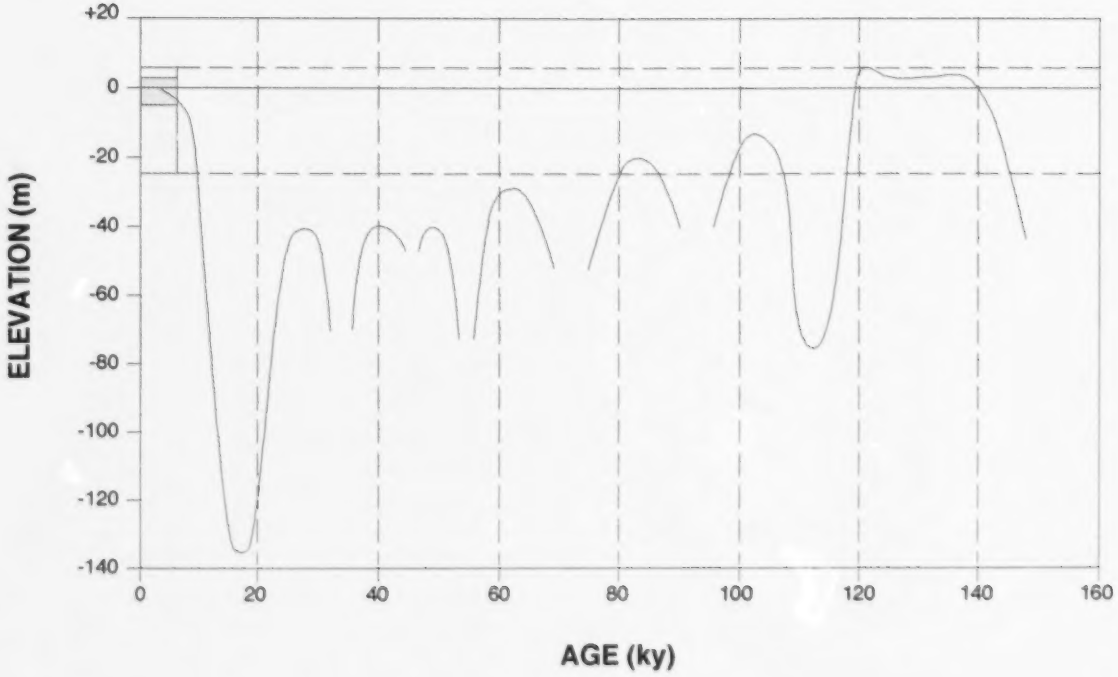


Figure V-1. Pleistocene sea level curve (after Moore 1982). The samples examined in this study were obtained from -3 to +4 m relative to present day sea level. These samples have been subaerially exposed and subjected to vadose diagenesis throughout most of their history. Phreatic diagenesis occurred for a brief period after deposition and during the last 4,000 to 5,000 years.

changes. The core between 1.5 and 15.3 m is dominantly composed of stable, low-magnesium calcite, whereas the rocks above and below this interval are mostly unstable aragonite and magnesium calcite.

These diagenetic zones are independent of lithologic and facies boundaries, and have been interpreted in terms of sea level highstands and lowstands, and the changes in diagenetic environments that accompanies them (Steinen and Matthews 1973). The rocks in the borehole were deposited during a high stand of the sea 105,000 years B.P., and were subaerially exposed shortly after deposition. During such lowstands of the sea (periods of glaciation) the entire column of rock was subjected to vadose diagenesis. During highstands of the sea (at 82,000 B.P., 60,000 B.P., and present) the rocks of the middle portion of the core were occupied by freshwater phreatic lenses that promoted rapid alteration of unstable mineralogy to low-magnesium calcite. Whereas the interval from 0 to 1.5 m has been in the vadose zone since shortly after its deposition, the rocks between 1.5 and 15.3 m have been subjected to alternate periods of vadose (lowstands) and phreatic (highstands) diagenesis. The rocks below 15.3 m have been exposed to the vadose environment during low stands of the sea and salt water during high stands.

The diagenetic history of the Pleistocene of Grand Cayman was controlled by the position of the formation relative to paleo-sea level (Figure V-1). Eustatic sea level changes during the late Pleistocene resulted in the movement of the formation through different diagenetic realms.

At the present day, the Ironshore Formation reaches a maximum height of +6.4 m above sea level (Jones and Hunter 1990), and is up to 30 m thick (Brunt *et al.* 1973). All samples examined in the present study were collected from Ironshore deposits ranging from +4 m to -3 m relative to present day sea level. The portion of the Ironshore Formation that is presently above sea level is currently subjected to vadose diagenesis, whereas that below sea level is affected by either marine phreatic, freshwater phreatic, or mixed saline and fresh diagenetic fluids. Although small, thin and isolated freshwater

aquifers are present in the Ironshore Formation (e.g. at Georgetown - Hunter 1992, pers. comm.), the major freshwater lenses of Grand Cayman are restricted to the underlying Bluff Formation (Ng 1990; Ng and Jones 1990; Ng *et al.* in press). As a result, no widespread freshwater meteoric diagenetic environment currently exists in the Ironshore Formation. In this respect, Grand Cayman differs from islands such as Barbados, which has an extensive freshwater aquifer approximately 9 m in thickness, developed within Pleistocene carbonates along the west coast (Tullstrom 1964; Matthews 1967; Harris 1971).

James and Choquette (1984) acknowledged that meteoric diagenesis on small islands with only local aquifers differs slightly from that of larger islands such as Bermuda, Jamaica and Barbados. Rates of diagenesis above and below the water table do not appear to be substantially different, and the degree of cementation decreases with depth in the phreatic zone as the proportion of sea water increases (Halley and Harris 1979; James and Choquette 1984).

The Ironshore Formation was deposited during a +6 m sea level highstand 125,000 years B.P. These rocks have been subaerially exposed and subjected to vadose diagenesis throughout most of their history. During sea level highstands, that occurred at 105,000, 82,000, 60,000 B.P and the present, the upper portion of the formation was (is) subjected to vadose conditions whereas the lower portion was (is) in the freshwater phreatic, marine phreatic or mixed diagenetic environment (Figure V-1B).

Although sea level history dictates that Pleistocene rocks have spent significantly more time in the vadose environment than in the phreatic, the Barbados data indicate that relatively short periods of exposure to freshwater phreatic fluids can result in rapid alteration of unstable mineralogy to stable mineralogy. With respect to the samples examined in this study (derived from the uppermost portion of the Ironshore Formation), it can be concluded that phreatic alteration has occurred only during the brief period following deposition and during the last 4000 to 5000 years (Figure V-1B).

C. USE OF TEXTURAL CRITERIA FOR DISTINGUISHING BETWEEN NEOMORPHIC SPAR AND CALCITE CEMENT

Carlson (1983) suggested that much of the difficulty in separating the products of *in situ* aragonite to calcite neomorphic transformation and dissolution/cementation (neomorphic spar and calcite cement, respectively) stems from the fact that these are not in fact two distinct processes, but rather they can be regarded as two end members of a spectrum of replacement. Similarly, Sandberg *et al.* (1973), and Sandberg (1984) argued that these processes differ only in scale and relative timing.

When viewed in this way, it is understandable that textural fabrics that result from these two types of transformation may be similar. Along the length of the spectrum is a range of processes involving varying degrees of void stage during alteration. Two aspects of the void stage are significant; the size of the void, and the length of time the void remains open before the new phase is precipitated. The length of time between dissolution and precipitation is extremely difficult to assess, thus the size of the void is generally used as an indicator of whether transformation has occurred by neomorphism, or dissolution followed by cementation.

The process of alteration via chalkification (James 1974; Pingitore 1976) can be regarded as intermediate between the two end members. Although significant amounts of void space are evident in the zone of aragonite chalk that lies at the contact between aragonite and replacement calcite, the original spherulitic texture of bundles of aragonite needles is preserved in ghost form (James 1974).

Bathurst's (1975) criteria are based mainly on morphology and arrangement of crystal mosaics and crystal boundaries, and are useful in distinguishing between neomorphic spar and cement only when the carbonate in question is examined with respect to all of the textural criteria. Extreme caution should be used in applying these criteria, and no single criterion should be used in interpretation of diagenetic product because there are countless examples where one or more of these textural requirements are not met. For example,

Land (1970) reported that phreatic meteoric cements from the Pleistocene at Devonshire Bay, Bermuda show no regular increase in size towards the center of the occluded pore, and the cement mosaic does not display good enfacial junctions. Similarly, Purdy (1968) noted that a regular vectorial increase in crystal size may occur in neomorphic calcite, and Steinen (1974) reported that calcite cements from the Pleistocene of Barbados show little tendency for increasing crystal size towards the interior parts of molds.

The single most reliable textural indicator that calcite is a neomorphic product is the inclusion of organic matter and oriented relics of the original aragonite. Such inclusions clearly demonstrate that aragonite to calcite transformation has occurred by thin film dissolution/reprecipitation. Numerous examples of such relics have been reported in both skeletal (Schneidermann *et al.* 1972; Sandberg *et al.* 1973; Sandberg 1975; Sandberg and Hudson 1983; Martin *et al.* 1986) and non-skeletal (Lasemi and Sandberg 1984) carbonate components.

It should be noted that the reporting of preserved relics is largely a function of the scale of observation. Ghosts of the original aragonite structure may be evident in thin section, but only under examination by SEM or TEM can the presence of aragonite crystals in the calcite be verified. Inclusion of organic matter, which provides the brownish color to neomorphic mosaics, is so finely disseminated that it is not recognizable on polished, etched surfaces examined on the SEM (Sandberg 1985).

Furthermore, in a given skeleton, neomorphic calcite and calcite cement are not mutually exclusive. The photomicrograph of Halley (1984, figure 3) shows a calcite replaced mollusc fragment from the Pleistocene Miami Limestone that contains: pore space created by dissolution of the original aragonite; calcite cement; and neomorphic calcite. It is unclear if neomorphism has occurred concomitantly with aragonite dissolution, or whether these processes are separated in time.

D. SIGNIFICANCE OF GROWTH ZONES IN NEOMORPHIC CALCITE

The occurrence of zoned calcite cements is common and has been documented from a wide range of carbonate rocks throughout the geologic column. In contrast, zoning of neomorphic calcite crystals has not been previously described.

Zones in calcite cements represent intracrystalline areas that differ in trace element, isotopic composition, and/or inclusion density. Cement zones are made visible by staining with potassium ferricyanide (Dickson 1965, 1966; Evamy and Shearman 1965; Oldershaw and Scoffin 1967; Davies and Till 1968; Colley and Davies 1969; Evamy 1969; Neal 1969), cathodoluminescence (Sippel and Glover 1965; Sippel 1968; Meyers 1974; Frank *et al.* 1982), and/or etching with HCl and examination at high magnifications.

Cement zones may consist of relatively simple concentric bands, or more irregular areas of the crystal (e.g. sector zoning - Reeder and Grams 1987). Parallel, concentric zones in cement reflect the past positions of former crystal faces and imply that sequential changes in fluid composition or growth rate have occurred during carbonate precipitation (Emery and Marshall 1989). Recent increases in the sophistication of analytical techniques have greatly improved the scale to which micro-zones in cement can be detected. This has led Emery and Marshall (1989) to conclude that the analysis of zoned calcite cements may have outpaced interpretation.

Neomorphic mosaics differ from cement in that growth zones and crystal interfaces are not planar. This textural dissimilarity can be attributed to differences in the style and mechanism of crystal growth, as displayed by the morphology and character of growth zones. Whereas the zones in calcite cement consist of regular, straight bands 3 to 6 μm wide, zones in neomorphic calcite of *Strombus gigas* consist of gently curving subparallel bands, 5 to 10 μm wide.

Planar interfaces between cement crystals are a result of nucleation of cement on free surfaces and competitive growth during increase in crystal size. Where adjacent crystals meet, they interrupt the freedom of each other's development, such that a planar interface is

maintained between them (Schmidegg 1928; Buckley 1951). Just as the straight, regular boundaries of cement zones are interpreted as representing the position of old crystal faces, the curved boundaries evident in neomorphic calcite may be regarded as the past positions of old neomorphic crystals. Crystal growth in neomorphic calcite takes place along a narrow neomorphic replacement front that passes through the skeleton. The interfaces between adjacent calcite crystals in the neomorphic mosaic are curved rather than planar, indicating that the process of competitive growth observed in cement precipitation does not occur during neomorphic replacement.

The presence of zones in neomorphic calcite can be viewed in terms of the 'two water system' proposed by Pingitore (1976, 1982). The thin film surface is narrow (< 1 μm) and is relatively isolated from the pore waters that surround the shell, thus chemical exchange between the fluid at the thin film surface with water percolating through the larger connected pores is intermittent and episodic. In contrast, the water from which cements are precipitated is in relatively constant contact with percolating waters. The greater width of the zones in neomorphic calcite may be a reflection of the relatively infrequent exchange between water at the neomorphic front with water that percolates through the rock, compared to that of the cement.

VI. CONCLUSIONS

1. Submarine diagenesis of *Strombus gigas* from Grand Cayman resulted in:
   a. encrustation and boring of the shell,
   b. accumulation of internal sediments in borings,
   c. precipitation of micrite cement on the wall of borings and surfaces of allochems, and
   d. submarine precipitation of pelsparite cement.

2. Subsequent exposure of *Strombus gigas* to the meteoric diagenetic environment resulted in:
   a. partial or complete inversion of the aragonitic shell to calcite,
   a. precipitation of blocky calcite spar cement, and
   b. near-surface precipitation of needle fibre calcite.

3. Alteration of *Strombus gigas* to calcite occurred by *in situ* dissolution of aragonite and reprecipitation of calcite across a thin solution film. The neomorphic calcite mosaic preserves the original microstructure of the shell in ghost form and includes relic oriented aragonite crystals and organic matter.

4. Neomorphic calcite crystals in *Strombus gigas* contain gently curving, subparallel zones 5-10 μm wide, that have not been previously documented. These zones are interpreted as having formed in response to slight changes in calcite chemistry (and hence solubility) caused by episodic fluid exchange between fluids at the thin film surface and waters percolating through the rock.

5. Submarine diagenesis of *Montastrea annularis* and *Siderastrea siderea* from Grand Cayman involved:
   a. precipitation of syntaxial aragonite cement,
   b. boring of the skeleton by worms, sponges, algae, fungi and *Lithophaga*,
   c. accumulation of sediment in borings and intraskeletal cavities, and
   d. precipitation of micrite and pelsparite cement.

6. Meteoric diagenesis of *Montastrea annularis* and *Siderastrea siderea* included:
   a. dissolution and / or alteration of aragonite needle cement,
   b. selective dissolution of the aragonitic skeleton,
   c. partial or complete mineralogical alteration of the skeleton to calcite,
   d. precipitation of blocky calcite spar in intraskeletal cavities,
   e. penetration by root systems, and
   f. precipitation of needle fibre calcite.

7. Mineralogical alteration of *Siderastrea siderea* and *Montastrea annularis* to calcite has proceeded by a combination of *in situ* neomorphic transformation, and larger scale dissolution of the skeleton and subsequent precipitation of calcite cement. No relic aragonite crystals are present, but inclusions of organic matter in the replacing calcite are common. The presence of micrite coatings on intraskeletal pores has promoted preservation of the skeletal structure of the corals.

8. Dissolution and subsequent calcitization of *Siderastrea siderea* and *Montastrea annularis* has proceeded by dissolution of aragonite and precipitation of calcite that begins along centers of calcification and proceeds outwards to pore walls.

9. Differences in resultant diagenetic texture of calcite replacement products in *Strombus gigas*, *Siderastrea siderea* and *Montastrea annularis* can be attributed to differences in skeletal structure (porosity and permeability) and microstructure (size, shape and arrangement of aragonite fibres) between these taxa.

10. Sea level history, hydrogeological data, and mineralogical and textural evidence indicate that the majority of alteration of these skeletal components has occurred in the vadose diagenetic environment.

VII. REFERENCES

ABBOTT, R.T. 1974. American Seashells: The Marine Mollusca of the Atlantic and Pacific Coasts of North America. Van Nostrand Reinhold Company Inc., New York, 663 p.

ACKER, K.L., and RISK, M.J. 1985. Substrate destruction and sediment production by the boring sponge *Cliona caribbaea* on Grand Cayman Island. Journal of Sedimentary Petrology, **55**: 701-711.

AHARON, P. 1983. 140,000-yr isotope climatic record from raised coral reefs in New Guinea. Nature, **304**: 720-723.

AISSAOUI, D.M., BUIGUES, D., and PURSER, B.H. 1986. Model of reef diagenesis: Mururoa Atoll, French Polynesia. *In* Reef Diagenesis. *Edited by* J.H. Schroeder and B.H. Purser. Springer Verlag, New York, p. 27-52.

ALEXANDERSSON, E.T. 1969. Recent littoral and sub-littoral high Mg-calcite lithification in the Mediterranean. Sedimentology, **12**: 47-61.

ALEXANDERSSON, E.T. 1972*a*. Intragranular growth of marine aragonite and Mg-calcite: Evidence of precipitation from supersaturated seawater. Journal of Sedimentary Petrology, **42**: 441-460.

ALEXANDERSSON, E.T. 1972*b*. Mediterranean beachrock cementation: Marine precipitation of Mg-calcite. *In* The Mediterranean Sea: A Natural Sedimentation Laboratory. *Edited by* D.J. Stanley. Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, p. 203-233.

ALEXANDERSSON, E.T. 1978. *Discussion of* Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point Panama (Macintyre 1977). Journal of Sedimentary Petrology, **48**: 665-668.

BAKER, P.A., and WEBER, J.N. 1975. Coral growth rate: Variation with depth. Earth and Planetary Science Letters, **27**: 57-61.

BANNER, F.T., and WOOD, G.V. 1964. Recrystallization in microfossiliferous limestones. Geological Journal, **4**: 1-34.

BATHURST, R.C.G. 1964. The replacement of aragonite by calcite in the molluscan shell wall. *In* Approaches to Paleoecology. *Edited by* J. Imbrie and N. Newell. John Wiley and Sons, New York, p. 357-376.

BARNES, D.J. 1970. Coral skeletons: An explanation of their growth and structure. Science, **170**: 1305-1308.

BATHURST, R.C.G. 1966. Boring algae, micrite envelopes, and lithification of molluscan biosparites. Geological Journal, **5**: 15-32.

BATHURST, R.C.G. 1975. Carbonate Sediments and Their Diagenesis. Developments in Sedimentology, No. 12, 2nd edition. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands, 658 p.

BØGGILD, O.B. 1930. The shell structure of the molluscs. Kongelige Danske Videnskabernes Selskab. Selskabs Skrifter 2, Naturvidenskabelig og Matematisk Afdeling, **2**: 231-326.

BROECKER, W.S., THURBER, D.L., GODDARD, J., KU, T.-L., MATTHEWS, R.K., and MESOLELLA, K.J. 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments. Science, **159**: 297-300.

BROMLEY, R.G. 1970. Borings as trace fossils and *Entobia cretacea* Portlock as an example. *In* Trace Fossils. *Edited by* T.P. Crimes and J.C. Harper. Geological Journal, Special Issue **3**: 49-90.

BROMLEY, R.G., and d'ALESSANDRO, A. 1984. The ichnogenus *Entobia* from the Miocene, Pliocene and Pleistocene of southern Italy. Rivista Italiana di Paleontogogia et Stratigraphie, **90**: 227-296.

BRUNI, S.F., and WENK, H.R. 1985. Replacement of aragonite by calcite in sediments from the San Cassiano Formation (Italy). Journal of Sedimentary Petrology, **55**: 159-170.

BRUNT, M.A., GIGLIOLI, M.E.C., MATHER, J.D., PIPER, D.J.W., and RICHARDS, H.G. 1973. The Pleistocene rocks of the Cayman Islands. Geological Magazine, **110**: 209-221.

BRYAN, W.H., and HILL, D. 1941. Spherulitic crystallization as a mechanism of skeletal growth in the hexacorals. Proceedings of the Royal Society of Queensland, **52**: 78-91.

BUCKLEY, H.E. 1951. Crystal Growth. John Wiley and Sons, New York, 571 p.

BUDDEMEIER, R.W., and KINZIE, R.A. 1976. Oceanography and Marine Biology Annual Reviews, **14**: 183-225.

BUDDEMEIER, R.W., MARAGOS, J.E., and KNUTSON, D.W. 1974. Radiographic studies of reef coral exoskeletons: Rates and patterns of coral growth. Journal of Experimental Marine Biology and Ecology, **14**: 179-200.

CALVET, F. 1982. Constructive micrite envelope developed in vadose continental environment in Pleistocene eoliantes of Mallorca (Spain). Acta Geologica Hispanica, **17**: 169-178.

CAREW, J.L., and MYLROIE, J.E. 1986. A refined geochronology for San Salvador Island, Bahamas. Proceedings of the 3rd Symposium on the Geology of the Bahamas, San Salvador Island, Bahamas, p. 35-44.

CAREW, J.L., MYLROIE, J., WEHMILLER, J.F., and LIVELY, R.S. 1984. Estimates of late Pleistocene sea level high stands from San Salvador, Bahamas. Proceedings of the 2nd Symposium on the Geology of the Bahamas, San Salvador Island, Bahamas, p. 153-175.

CARLSON, W.D. 1983. The polymorphs of $CaCO_3$ and the aragonite - calcite transformation. *In* Carbonates: Mineralogy and Chemistry. *Edited by* R.J. Reeder. Mineralogical Society of America, Reviews in Mineralogy **11**: 191-225.

CERRIDWEN, S. 1989. Paleoecology of Pleistocene molluscs from the Ironshore Formation, Grand Cayman, B.W.I. Unpublished M.Sc. thesis, University of Alberta, Edmonton, Alberta, 271 p.

CHAFETZ, H.S. 1986. Marine peloids: A product of bacterially induced precipitation of calcite. Journal of Sedimentary Petrology, **56**: 812-817.

CHAVE, K.E., DEFFEYES, K.S., WEYLK, P.K., GARRELS, R.L., and THOMPSON, M.E. 1962. Observations on the solubility of skeletal carbonates in aqueous solutions. Science, **137**: 33-34.

CHAFETZ, H.S., MCINTOSH, A.G., and RUSH, P.F. 1988. Fresh-water phreatic diagenesis in the marine realm of Recent Arabian Gulf carbonates. Journal of Sedimentary Petrology, **58**: 433-440.

CHAVE, K.E., and SCHMALZ, R.F. 1966. Carbonate-seawater reactions. Geochimica et Cosmochimica Acta, **30**: 1037-1048.

CHEN, J.H., CURRAN, H.A., WHITE, B., and WASSERBURG, G.J. 1991. Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas. Geological Society of America Bulletin, **103**: 82-97.

CLARK, S.P. 1957. A note on calcite - aragonite equilibrium. American Mineralogist, **42**: 564-566.

CLENCH, W.J., and ABBOTT, R.T. 1941. The genus *Strombus* in the western Atlantic. Johnsonia, **1**: 1-15.

COBB, W.R. 1969. Penetration of calcium carbonate substrates by the boring sponge *Cliona*. American Zoologist, **9**: 783-790.

COLLEY, H., and DAVIES, P.J. 1969. Ferroan and non-ferroan calcite cements in Pleistocene-Recent carbonates from the New Hebrides. Journal of Sedimentary Petrology, **39**: 554-558.

CONGLIO, M., JAMES, N.P., and AISSAOUI, D.M. 1988. Dolomitization of Miocene carbonates, Gulf of Suez, Egypt. Journal of Sedimentary Petrology, **58**: 100-119.

CONSTANZ, B. 1985. Taxon-specific diagenetic variation among scleractinian corals (Barbados, West Indies). Proceedings of the Fifth International Coral Reef Congress, Tahiti, **3**: 229-234.

DAVIES, P.J., and TILL, R. 1968. Stained dry cellulose peels of ancient and Recent impregnated carbonate sediments. Journal of Sedimentary Petrology, **38**: 234-237.

DICKSON, J.A.D. 1965. A modified staining technique for carbonates in thin section. Nature, **25**: 287.

DICKSON, J.A.D. 1966. Carbonate identification and genesis as revealed by staining. Journal of Sedimentary Petrology, **36**: 491-505.

DIGERFELDT, G., and HENDRY, M.D. 1987. An 8000 year sea-level record from Jamaica: Implications for interpretation of Caribbean reef and coastal history. Coral Reefs, **5**: 165-169.

DODD, J.R. 1966. Processes of conversion of aragonite to calcite with examples from the Cretaceous of Texas. Journal of Sedimentary Petrology, **36**: 733-741.

DUERDEN, J.E. 1904. The coral *Siderastrea radians* and its postlarval development. Carnegie Institute of Washington, Publication **20**, 130 p.

EKDALE, A.A., BROMLEY, R.G., and PEMBERTON, S.G. 1984. Ichnology: Trace fossils in sedimentology and stratigraphy. Society of Economic Paleontologists and Mineralogists, Short Course Notes **15**, 317 p.

EMERY, D., and MARSHALL, J.D. 1989. Zoned calcite cements: Has analysis outpaced interpretation? Sedimentary Geology, **65**: 205-210.

EMERY, K.O. 1981. Low marine terraces of Grand Cayman Island. Estuarine, Coastal and Shelf Sciences, **12**: 569-578.

EVAMY, B.D. 1969. The precipitational environment and correlation of some calcite cements deduced from artificial staining. Journal of Sedimentary Petrology, **39**: 787-793.

EVAMY, B.D., and SHEARMAN, D.J. 1965. The development of overgrowths from echinoderm fragments. Sedimentology, **5**: 211-233.

FEIGL, F. 1937. Qualitative Analysis by Spot Tests. Nordemann Publishing Company, New York, 400 p.

FOLK, R.L. 1959. Practical petrographic classification of limestones. Bulletin of the American Association of Petroleum Geologists, **43**: 1-38.

FOLK, R.L. 1965. Some aspects of recrystallization in ancient limestones. *In* Dolomitization and Limestone Diagenesis: A Symposium. *Edited by* L.C. Pray and R.C. Murray. Society of Economic Paleontologists and Mineralogists, Special Publication **13**: 14-48.

FOLK, R.L., and ASSERTO, R. 1976. Comparative fabrics of length-slow and length-fast calcite and calcitized aragonite in a Holocene speleothem, Carlsbad Caverns, New Mexico. Journal of Sedimentolgy, **46**: 486-496.

FRANK, J.R., CARPENTER, A.B., and OGLESBY, T.W. 1982. Cathodoluminescence and composition of calcite cement in the Taum Sauk Limestone (Upper Cambrian), southeast Missouri. Journal of Sedimentary Petrology, **52**: 631-638.

FRIEDMAN, G.M. 1964. Early diagenesis and lithification in carbonate sediments. Journal of Sedimentary Petrology, **34**: 777-813.

FRIEDMAN, G.M. 1985*a*. The problem of submarine cement in classifying reefrock: An experience in frustration. *In* Carbonate Cements. *Edited by* N. Schneidermann and P.M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication **36**: 117-121.

FRIEDMAN, G.M. 1985*b*. The term *micrite* or *micrite cement* is a contradiction. *Discussion of* Micrite cement in microborings is not necessarily a shallow-water indicator. Journal of Sedimentary Petrology, **55**: 777.

FRIEDMAN, G.M., AMIEL, A.J., and SCHNEIDERMANN, N. 1974. Submarine cementation in reefs: Example from the Red Sea. Journal of Sedimentary Petrology, **44**: 816-825.

FRIEDMAN, G.M., GEBELEIN, C.D., and SANDERS, J.E. 1971. Micrite envelopes of carbonate grains are not exclusively of photosynthethic algal origin. Sedimentology, **16**: 89-96.

FRIEDMAN, G.M., and SANDERS, J.E. 1978. Principles of Sedimentology. John Wiley and Sons, New York, 792 p.

FUTTERER, D.K. 1974. Significance of the boring sponge *Cliona* for the origin of fine-grained material for carbonate sediments. Journal of Sedimentary Petrology, **44**: 79-84.

FYFE, W.S., and BISCHOFF, J.L. 1965. The calcite - aragonite problem. *In* Dolomitization and Limestone Diagenesis: A Symposium. *Edited by* L.C. Pray and R.C. Murray. Society of Economic Paleontologists and Mineralogists, Special Publication **13**: 3-13.

GALEHOUSE, J.S. 1971. Point counting. *In* Procedures in Sedimentary Petrology. *Edited by* R.E. Carver. Wiley-Interscience, New York, p. 385-407.

GINSBURG, R.N. 1957. Early diagenesis and lithification of shallow water carbonate sediments in south Florida. *In* Regional Aspects of Carbonate Deposition. *Edited by* R.J. LeBlanc and J.G. Breeding. Society of Economic Paleontologists and Mineralogists, Special Publication **5**: 80-99.

GINSBURG, R.N. 1973. Geological and biological roles of cavities in coral reefs. *In* Perspectives on Coral Reefs. *Edited by* D.J. Barnes. Clouston, Canberra, p. 231-239.

GINSBURG, R.N., MARSZALEK, D.S., and SCHNEIDERMANN, N. 1971. Ultrastructure of carbonate cements in a Holocene algal reef of Bermuda. Journal of Sedimentary Petrology, **41**: 472-482.

GINSBURG, R.N., and SCHROEDER, J.H. 1973. Growth and submarine fossilization of algal cup reefs, Bermuda. Sedimentology, **20**: 575-614.

GLADFELTER, E.H., MONAHAN, R.K., and GLADFELTER, W.B. 1978. Growth rates of five reef-building corals in the northeastern Caribbean. Bulletin of Marine Science, **28**: 728-734.

GOREAU, T.F. 1977. Coral skeletal chemistry: Physiological and environmental regulation of stable isotopes and trace metals in *Montastrea annularis*. Proceedings of the Royal Society of London, **196**: 291-315.

GOREAU, T.F., and WELLS, J.W. 1967. The shallow water Scleractinia of Jamaica: Revised list of species and their vertical distribution range. Bulletin of Marine Science, **17**: 442-453.

GVIRTZMAN, G., and FRIEDMAN, G.M. 1977. Sequence of progressive diagenesis in coral reefs. *In* Reef and Related Carbonates: Ecology and Sedimentology. *Edited by* S.H. Frost, M.P. Weiss, and J.B. Saunders. American Association of Petroleum Geologists, Studies in Geology **4**: 357-380.

HADFIELD, M.G. 1976. Molluscs associated with living tropical corals. Micronesica, **12**: 133-148.

HALLEY, R.B. 1984. Post-depositional diagenesis of metastable carbonates: An overview. Palaeontographica Americana, **54**: 245-253.

HALLEY, R.B., and HARRIS, P.M. 1979. Freshwater cementation of a 1000-year old oolite. Journal of Sedimentary Petrology, **49**: 969-988.

HARMON, R.S., SCHWARCZ, H.P., and FORD, D. 1978. Late Pleistocene sea level history of Bermuda. Quaternary Research, 9: 205-218.

HARMON, R.S., LAND, L.S., MITTERER, R.M., GARRETT, P., SCHWARCZ, H.P., and LARSON, G.J. 1981. Bermuda sea level during the last interglacial. Nature, **289**: 481-483.

HARMON, R.S., SCHWARCZ, H.P., and FORD, D. 1978. Late Pleistocene sea level history of Bermuda. Quaternary Research, **9**: 205-218.

HARRIS, W.H. 1971. Ground Water-Carbonate Rock Chemical Interactions, Barbados, West Indies. Unpublished Ph.D. thesis, Brown University, Providence, Rhode Island, 348 p.

HARRIS, W.H., and MATTHEWS, R.K. 1968. Subaerial diagenesis of carbonate sediments: Efficiency of the solution reprecipitation process. Science, **160**: 77-79.

HARRISON, R.S. 1974. Near-surface Subaerial Diagenesis of Pleistocene Carbonates, Barbados, West Indies. Unpublished Ph.D. thesis, Brown University, Providence, Rhode Island, 333 p.

HARRISON, R.S. 1977. Subaerial versus submarine discontinuity surfaces in a Pleistocene reef complex, Barbados, W.I. Proceedings of the 3rd International Coral Reef Symposium, Miami, **2**: 143-147.

HOOK, J.A., GOLUBIC, S., AND MILLIMAN, J.D. 1984. Micritic cement in microborings is not necessarily a shallow-water indicator. Journal of Sedimentary Petrology, **54**: 425-431.

HUBBARD, D.K., and SCATURO, D. 1985. Growth rates of seven species of scleractinian corals from Cane Bay and Salt River, St. Croix, USVI. Bulletin of Marine Science, **36**: 325-338.

HUBBARD, J.A.E.B. 1975. Life and afterlife of reef corals: A timed study of incipient diagenesis. Abstracts of the 11th International Sedimentological Congress, Nice, France, **7**: 75-80.

HUBBARD, J.A.E.B., and POCOCK, Y.P. 1972. Sediment rejection by recent scleractinian corals: A key to paleo-environmental reconstruction. Geologische Rundschau, **61**, 598-626.

HUDSON, J.H., SHINN, E.A., HALLEY, R.B., LIDZ, B. 1976. Sclerochronology: A tool for interpreting past environments. Geology, **4**: 361.

HUNTER, I.G., and JONES, B. 1988. Corals and paleogeography of the Pleistocene Ironshore Formation on Grand Cayman, B.W.I. Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia, **3**: 431-440.

HUNTER, I.G., and JONES, B. 1989. Sedimentology of the late Pleistocene Ironshore Formation on Grand Cayman. Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S. Virgin Islands, p. 115-124.

JAMES, N.P. 1970. Role of boring organisms in the coral reefs of the Bermuda Platform. *In* Seminar on Organism-Sediment Interrelationships. *Edited by* R.N. Ginsburg and S.M. Stanley. Bermuda Biological Station for Research, Special Publication **6**: 19-28.

JAMES, N.P. 1972*a*. Late Pleistocene Reef Limestones, Northern Barbados, West Indies. Unpublished Ph.D. thesis, McGill University, Montreal, Quebec, 282 p.

JAMES, N.P. 1972*b*. Holocene and Pleistocene calcareous crust (caliche) profiles: criteria for sub-aerial exposure. Journal of Sedmentary Petrology, **42**: 817-836.

JAMES, N.P. 1974. Diagenesis of scleractinian corals in the subaerial vadose environment. Journal of Paleontology, **48**: 785-799.

JAMES, N.P., and CHOQUETTE, P.W. 1983. Limestone diagenesis 6: The seafloor diagenetic environment. Geoscience Canada, **10**: 162-179.

JAMES, N.P., and CHOQUETTE, P.W. 1984. Limestone diagenesis 9: Limestones - The meteoric diagenetic environment. Geoscience Canada, **11**: 161-194.

JAMES, N.P., and GINSBURG, R.N. 1979. The seaward margin of Belize barrier and atoll reefs. International Association of Sedimentologists, Special Publication **3**: 191 p.

JAMES, N.P., GINSBURG, R.N., MARSZALEK, D., and CHOQUETTE, P.W. 1976. Facies and fabric specificity of early subsea cementation in shallow Belize (British Honduras) reefs. Journal of Sedimentary Petrology, **46**: 523-544.

JAMIESON, J.C. 1953. Phase equilibrium in the system calcite - aragonite. Journal of Chemistry and Physics, **21**: 1385-1390.

JAVIDPOUR, M. 1978. Fossil *Strombus gigas* from southern Florida. Nautilus, **92**: 102-104.

JONES, B. 1987. The alteration of sparry calcite crystals in a vadose setting, Grand Cayman Island. Canadian Journal of Earth Sciences, **24**: 2292-2304.

JONES, B. 1989. Calcite rafts, peloids, and micrite in cave deposits from Cayman Brac, British West Indies. Canadian Journal of Earth Sciences, **26**: 654-664.

JONES, B. 1990. Tunicate spicules and their syntaxial overgrowths: Examples from the Pleistocene Ironshore Formation, Grand Cayman, British West Indies. Canadian Journal of Earth Sciences, **27**: 525-532.

JONES, B., and HUNTER, I.G. 1989. The Oligocene-Miocene Bluff Formation on Grand Cayman. Caribbean Journal of Science, **25**: 71-85.

JONES, B., and HUNTER, I.G. 1990. Pleistocene paleogeography and sea levels on the Cayman Islands, British West Indies. Coral Reefs, **9**: 81-91.

JONES, B., LOCKHART, E.B., and SQUAIR, C. 1984. Phreatic and vadose cements in the Tertiary Bluff Formation of Grand Cayman Island, British West Indies. Bulletin of Canadian Petroleum Geology, **32**: 382-397.

JONES, B., and NG, K. 1988. The structure and diagenesis of rhizoliths from Cayman Brac, British West Indies. Journal of Sedimentary Petrology, **58**: 457-467.

JONES, B., and PEMBERTON, S. G. 1988*a*. Bioerosion of corals by *Lithophaga*: Example from the Pleistocene Ironshore Formation of Grand Cayman, B.W.I. Proceedings of the 6th International Coral Reef Symposium, Australia, **3**: 437-440.

JONES, B., and PEMBERTON, S.G. 1988*b*. *Lithophaga* borings and their influence on the diagenesis of corals in the Pleistocene Ironshore Formation of Grand Cayman Island, British West Indies. Palaios, **3**: 3-21.

JONES, B., and PEMBERTON, S.G. 1989. Sedimentology and ichnology of a Pleistocene unconformity bounded shallowing upward carbonate sequence: The Ironshore Formation, Salt Creek, Grand Cayman. Palaios, **4**: 343-355.

JONES, B., and SMITH, D.S. 1988. Open and filled karst features on the Cayman Islands: Implications for the recognition of paleokarst. Canadian Journal of Earth Sciences, **25**: 1277-1291.

KELLY, S.R.A., and BROMLEY, R.G. 1984. Ichnological nomenclature of clavate borings. Palaeontology, **27**: 793-807.

KENDALL, C.G., and SKIPWORTH, P.A. 1969. Holocene shallow-water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf. Bulletin of the American Association of Petroleum Geologists, **53**: 841-869.

KENNEDY, W.J., and KLINGER, H.C. 1972. Hiatus concretions and hardground horizons in the Cretaceous of Zululand (South Africa). Palaeontology, **15**: 539-549.

KINSMAN, D.J.J. 1969. Interpretation of Sr^{2+} concentrations in carbonate minerals and rocks. Journal of Sedimentary Petrology, **39**: 486-508.

KNUTSON, D.W., BUDDEMEIER, R.W., and SMITH, S.V. 1972. Coral chronometers: Seasonal growth bands in reef corals. Science, 1977: 270-272.

KOBLUK, D.R., and RISK, M.J. 1977*a*. Calcification of exposed filaments of endolithic algae, micrite envelope formation and sediment production. Journal of Sedimentary Petrology, **47**: 517-528.

KOBLUK, D.R., and RISK, M.J. 1977*b*. Micritization and carbonate grain binding by endolithic algae. Bulletin of the American Association of Petroleum Geologists, **61**: 1069-1082.

LAND, L.S. 1967. Diagenesis of skeletal carbonates. Journal of Sedimentary Petrology, **37**: 914-930.

LAND, L.S. 1970. Phreatic versus vadose meteoric diagenesis of limestones: Evidence from a fossil water table. Sedimentology, **14**: 175-185.

LAND, L.S. 1971. Submarine lithification of Jamaican reefs. *In* Carbonate Cements. *Edited by* O.P. Bricker. John Hopkins University Press, Studies in Geology **19**: 59-62.

LAND, L.S., and GOREAU, T.F. 1970. Submarine lithification of Jamaican reefs. Journal of Sedimentary Petrology, **40**: 457-462.

LAND, L.S., MACKENZIE, F.T., and GOULD, S.J. 1967. Pleistocene history of Bermuda. Geological Society of America Bulletin, **78**: 993-1006.

LAND, L.S., and MOORE, C.H. 1980. Lithification, micritization and syndepositional diagenesis of biolithities on the Jamaican island slope. Journal of Sedimentary Petrology, **50**: 357-370.

LASEMI, Z., and SANDBERG, P.A. 1984. Transformation of aragonite-dominated lime muds to microcrystalline limestones. Geology, **12**: 420-423.

LAWRENCE, D.R. 1969. The use of clionid sponges in paleoenvironmental analyses. Journal of Paleontology, **43**: 539-543.

LIGHTY, R.G. 1985. Preservation of internal reef porosity and diagenetic sealing of submerged early Holocene barrier reef, southeast Florida shelf. *In* Carbonate Cements. *Edited by* N. Schneidermann, and P.M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication **36**: 123-151.

LONGMAN, M.W. 1980. Carbonate diagenetic textures from nearsurface diagenetic environments. Bulletin of the American Association of Petroleum Geologists, **64**: 461-487.

MACINTYRE, I.G. 1977. Distribution of submarine cements in a modern Caribbean fringing reef, Galeta Point, Panama. Journal of Sedimentary Petrology, **47**: 503-516.

MACINTYRE, I.G. 1985. Submarine cements: The peloidal question. *In* Carbonate Cements. *Edited by* N. Schneidermann, and P.M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication **36**: 109-116.

MACINTYRE, I.G., and MARSHALL, J.F. 1988. Submarine lithification in coral reefs: Some facts and misconceptions. Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia, **1**: 263-272.

MACINTYRE, I.G., MOUNTJOY, E.W., and d'ANGLEJAN, B.F. 1968. An occurrence of submarine cementation of carbonate sediments off the west coast of Barbados, W.I. Journal of Sedimentary Petrology, **38**: 660-664.

MACINTYRE, I.G., and VIDETICH, P.E. 1979. Pseudostalactites from submarine cave near Columbus Cay, Belize barrier-reef complex: Evidence of extensive submarine lithification. Bulletin of the American Association of Petroleum Geologists, **63**: 489 (Abstract).

MARSHALL, J.F. 1983. Submarine cementation in a high-energy platform reef: One Tree Reef, southern Great Barrier Reef. Journal of Sedimentary Petrology, **53**: 1133-1149.

MARSHALL, J.F., and DAVIES, P.J. 1981. Submarine lithification on windward reef slopes: Capricorn-Bunker Group, southern Great Barrier Reef. Journal of Sedimentary Petrology, **51**: 933-960.

MARTIN, G.D., WILKINSON, B.H., and LOHMANN, K.C. 1986. The role of skeletal porosity in aragonite neomorphism: *Strombus* and *Montastrea* from the Pleistocene Key Largo Limestone, Florida. Journal of Sedimentary Petrology, **56**: 194-203.

MATTHEWS, R.K. 1967. Diagenetic fabrics in biosparites from the Pleistocene of Barbados, West Indies. Journal of Sedimentary Petrology, **37**: 1147-1153.

MATTHEWS, R.K. 1968. Carbonate diagenesis: Equilibration of sedimentary mineralogy to the subaerial environment; Coral cap of Barbados, West Indies. Journal of Sedimentary Petrology, **38**: 1110-1119.

MATTHEWS, R.K. 1973. Relative elevation of late Pleistocene high sea level stands: Barbados uplift rates and their implication. Quaternary Research, **3**: 147-153.

MATTHEWS, R.K. 1974. A process approach to diagenesis of reefs and reef associated limestones. *In* Reefs in Time and Space. *Edited by* L.F. LaPorte. Society of Economic Paleontologists and Mineralogists, Special Publication **18**: 234-256.

MATLEY, C.A. 1926. The geology of the Cayman Islands (British West Indies) and their relation to the Bartlett Trough. Quarterly Journal of the Geological Society of London, **82**: 352-386.

MCKEE, E.D., and GUTSCHICK, R.C. 1969. History of Redwall Limestone of northern Arizona. Geological Society of America, Memoir **114**: 1-726.

MESOLELLA, K.J., MATTHEWS, R.K., BROECKER, W.S., and THURBER, D.L. 1969. The astronomical theory of climatic change: Barbados data. Journal of Geology, **77**: 250-274.

MESOLELLA, K.J., SEALY, H.A., and MATTHEWS, R.K. 1970. Facies geometries within Pleistocene reefs of Barbados, West Indies. Bulletin of the American Association of Petroleum Geologists, **54**: 1899-1917.

MEYERS, W.J. 1974. Carbonate stratigraphy of the Lake Valley Formation (Mississippian), Sacremento Mountains, New Mexico. Journal of Sedimentary Petrology, **44**: 837-861.

MILLIMAN, J.D. 1974. Marine Carbonates. Springer Verlag, New York, 375 p.

MILLIMAN, J.D., HOOK, J.A., and GOLUBIC, S. 1985. *Reply to Discussion* Meaning and usage of *micrite cement* and *matrix*. Journal of Sedimentary Petrology, **55**: 893-900.

MOORE, W.S. 1982. Late Pleistocene sea-level history. *In* Uranium Series Disequilibrium: Application to Environmental Problems. *Edited by* M. Ivanovich and R.S. Harmon. Carendon Press, Oxford, p. 482-496.

NAKAHARA, H., KAKEI, M., and BEVELANDER, G. 1981. Studies on the formation of the crossed lamellar structure in the shell of *Strombus gigas*. The Veliger, **23**: 207-211.

NEAL, W.J. 1969. Diagenesis and dolomitization of a limestone (Pennsylvanian of Missouri) as revealed by staining. Journal of Sedimentary Petrology, **39**: 1040-1045.

NEUMANN, A.C., and MOORE, W.S. 1975. Sea level events and Pleistocene coral ages in the northern Bahamas. Quaternary Research, **5**: 215-224.

NG, K.-C. 1990. Diagenesis of the Oligocene-Miocene Bluff Formation of the Cayman Islands: A Petrographic and Hydrogeochemical Approach. Unpublished Ph.D. thesis, University of Alberta, Edmonton, Alberta, 344 p.

NG, K.-C., and JONES, B. 1990. Chemical and stable isotopic characteristics of ground water on Grand Cayman. Tropical Hydrology and Caribbean Water Resources, July: 411-420.

NG, K.-C., JONES, B., and BESWICK, R. In Press. Hydrogeology of a karstic dolostone aquifer on Grand Cayman, British West Indies. Journal of Hydrology.

OLDERSHAW, A.E., and SCOFFIN, T.P. 1967. The source of ferroan and non-ferroan calcite cements in the Halkin and Wenlock Limestones. Geological Journal, **5**: 309-320.

OTTER, G.W. 1937. Rock-destroying organisms in relation to coral reefs. Great Barrier Reef Expedition 1928-1929, British Museum of Natural History, **1**: 324-351.

PEMBERTON, S.G., and JONES, B. 1988. Ichnology of the Pleistocene Ironshore Formation, Grand Cayman Island, British West Indies. Journal of Paleontology, **62**: 495-505.

PIERSON, B.J., and SHINN, E.A. 1985. Cement distribution and carbonate mineral stabilization in Pleistocene limestones of Hogsty Reef, Bahamas. *In* Carbonate Cements. *Edited by* N. Schneidermann and P.M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication **36**: 153-168.

PINGITORE, N.E. 1970. Diagenesis and porosity modification in *Acropora palamata*, Pleistocene of Barbados, West Indies. Journal of Sedimentary Petrology, **40**: 712-721.

PINGITORE, N.E. 1976. Vadose and phreatic diagenesis: Processes, products and their recognition in corals. Journal of Sedimentary Petrology, **46**: 985-1006.

PINGITORE, N.E. 1982. The role of diffusion during carbonate diagenesis. Journal of Sedimentary Petrology, **52**: 27-39.

PITTMAN, E.D. 1974. Porosity and permeability changes during diagenesis of Pleistocene corals, Barbados, West Indies. Geological Society of America Bulletin, **85**: 1811-1820.

PLEYDELL, S.M., and JONES, B. 1988. Boring of various faunal elements in the Oligocene-Miocene Bluff Formation of Grand Cayman, British West Indies. Journal of Paleontology, **62**: 348-367.

POMPONI, S.A. 1977. Etching cells of boring sponges: An ultrastructural analysis. Proceedings of the 3rd International Coral Reef Symposium, University of Miami, Miami, Florida, **2**: 485-490.

PURDY, E.G. 1968. Carbonate diagenesis: An environmental survey. Geologica Romana, **7**: 183-228.

RANDALL, J.E. 1964. Contributions to the biology of the queen conch, *Strombus gigas.* Bulletin of Marine Science of the Gulf and Caribbean, **14:** 246-295.

REEDER, R.J., and GRAMS, J.C. 1987. Sector zoning in calcite cement crystals: Implications for trace element distributions in carbonates. Geochimica et Cosmochimica Acta, **51**: 187-194.

RIGBY, J.K., and ROBERTS, H.H. 1976. Geology, reefs and marine communities of Grand Cayman Island, British West Indies. Brigham Young University, Geological Studies, Special Publication **4**: 1-95.

RISK, M.J., and MACGEACHY, J.K. 1978. Aspects of bioerosion of modern Caribbean reefs. Revista de Biologica Tropical, **26**: 85-105.

RUTZLER, K. 1974. The burrowing sponges of Bermuda. Smithsonian Contributions to Zoology, **165**: 1-32.

RUTZLER, K. 1975. The role of burrowing sponges in bioersion. Oecologia, **19**: 203-216.

RUTZLER, K., and RIEGER, G. 1973. Sponge burrowing: Fine structure of *Cliona lampa* penetrating calcareous substrate. Marine Biology, **21**: 144-162.

SANDBERG, P.A. 1975. Bryozoan diagenesis: Bearing on the nature of the original skeleton of rugose corals. Journal of Paleontology, **49**: 587-606.

SANDBERG, P.A. 1984. Recognition criteria for calcitized skeletal and non-skeletal aragonites. Palaeontographica Americana, **54**: 272-281.

SANDBERG, P.A. 1985. Aragonite cements and their occurrence in ancient limestone. *In* Carbonate Cements. *Edited by* N. Schneidermann and P.M. Harris. Society of Economic Paleontologists and Mineralogists, Special Publication **36**: 33-58.

SANDBERG, P.A., and HUDSON, J.D. 1983. Aragonite relic preservation in Jurassic calcite-replaced bivalves. Sedimentology, **30**: 879-892.

SANDBERG, P.A., SCHNEIDERMANN, N., and WUNDER, S.J. 1973. Aragonite ultrastructural relics in calcite-replaced Pleistocene skeletons. Nature Physical Science, **245**: 133-134.

SCHERER, M. 1974. Submarine recrystallization of a coral skeleton in a Holocene Bahamian reef. Geology, **2**: 499-500.

SCHLANGER, S.O. 1963. Subsurface geology of Eniwetok Atoll. United States Geological Survey, Professional Paper **260BB**: 991-1066.

SCHLANGER, S.O. 1964. Petrology of the limestones of Guam. United States Geological Survey, Professional Paper **405D**, 52 p.

SCHMIDEGG, O. 1928. Über geregelte Waschstumsgefüge. Jahrbuch Geologie Bundesanstalt, **78**: 1-52.

SCHNEIDERMANN, N., SANDBERG, P.A., and WUNDER, S.J. 1972. Recognition of early cementation of aragonite skeletal carbonates. Nature Physical Science, **240**: 88-89.

SCHROEDER, J.H. 1972. Calcified filaments of an endolithic alga in Recent Bermuda reefs. Neues Jahrbuch Geologie Palaontologie Montatshefte, **1**: 16-33.

SCHROEDER, J.H. 1973. Submarine and vadose cements in Pleistocene Bermuda reef rock. Sedimentary Geology, **10**: 179-204.

SCOFFIN, T.P. 1987. An Introduction to Carbonate Sediments and Rocks. Chapman and Hall, New York, 274 p.

SCOFFIN, T.P., and GARRET, P. 1974. Processes in formation and preservation of internal structure in Bermuda Patch Reefs. Proceedings of the 2nd International Coral Reef Symposium, Brisbane, Australia, **2**: 429-448.

SHINN, E.A. 1969. Submarine lithification of Holocene carbonate sediments in the Persian Gulf. Sedimentology, **12**: 109-144.

SIBLEY, D.F. 1980. Climatic control of dolomitization, Seroe Domi Formation (Pliocene), Bonaire, N.A. *In* Concepts and Models of Dolomitization. *Edited by* D.H. Zenger, J.B. Dunham, and R.L. Ethinton. Society of Economic Paleontologists and Mineralogists, Special Publication **28**: 247-258.

SIBLEY, D.F., and MURRAY, R.C. 1972. Marine diagenesis of carbonate sediment, Bonaire, Netherlands Antilles. Journal of Sedimentary Petrology, **42**: 168-178.

SIPPEL, R.F. 1968. Sandstone petrology, evidence from luminescence petrography. Journal of Sedimentary Petrology, **38**: 530-554.

SIPPEL, R.F., and GLOVER, E.D. 1965. Structures in carbonate rocks made visible by luminescence petrography. Science, **150**: 1283-1287.

SPIRO, B.F., and HANSEN, F.J. 1970. Diagenesis of some scleractinian corals from the Gulf of Elat, Israel. Bulletin of the Geological Society of Denmark, **21**: 1-10.

STEARN, C.E. 1976. Estimates of the position of sea level between 140,000 and 75,000 years ago. Quaternary Research, **6**: 445-449.

STEHLI, F.G., and HOWER, J. 1961. Mineralogy and early diagenesis of carbonate sediments. Journal of Sedimentary Petrology, **31**: 358-371.

STEINEN, R.P. 1974. Phreatic and vadose diagenetic modification of Pleistocene Limestone: Petrographic observations from subsurface of Barbados, West Indies. Bulletin of the American Association of Petroleum Geologists, **58**: 1008-1024.

STEINEN, R.P., HARRISON, R.S., and MATTHEWS, R.K. 1973. Eustatic low stand of sea level between 125,000 and 105,000 B.P.: Evidence from the subsurface of Barbados, West Indies. Geological Society of America Bulletin, **84**: 63-70.

STEINEN, R.P., and MATTHEWS, R.K. 1973. Phreatic versus vadose diagenesis: Stratigraphy and mineralogy of a cored borehole on Barbados, W.I. Journal of Sedimentary Petrology, **43**: 1012-1020.

STOWERS, R.E., MYLROIE, J.E., and CAREW, J.L. 1988. Pleistocene stratigraphy and geochronology southwestern San Salvador Island, Bahamas. Proceedings of the 4th Symposium on the Geology of the Bahamas, San Salvador Island, Bahamas, p. 323-330.

SUPKO, P.R. 1971. 'Whisker' crystal calcite cement in a Bahamian rock. *In* Carbonate Cements. *Edited by* O.P. Bricker. John Hopkins University Press, Studies in Geology **19**: 143-149.

TAYLOR, J.C.M., and ILLING, L.V. 1969. Holocene intertidal calcium carbonate cementation, Qatar, Persian Gulf. Sedimentology, **12**: 69-107.

TAYLOR, J.D., KENNEDY, W.J., and HALL, A. 1969. The shell structure and mineralogy of the Bivalvia: Introduction Nuculacea-Trigonacea. Bulletin of the British Museum of Zoology, Supplement **3:** 1-125.

TEBBUTT, G.E. 1967. Diagenesis of Pleistocene Limestone on Ambergris Cay, British Honduras. Unpublished Ph.D. thesis, Rice University, Houston, Texas, 133 p.

TEBBUTT, G.E. 1975. Paleoecology and diagenesis of Pleistocene limestone on Ambergris Cay. *In* Belize Shelf: Carbonate Sediments, Clastic Sediments, and Ecology. *Edited by* K.W. Wantland and W.C. Pusey. American Association of Petroleum Geologists, Studies in Geology **2**: 315-328.

TULLSTROM, H. 1964. Report on the water supply of Barbados. Report to the Government of Barbados, U.N. Programme of Technical Assistance, Publication **64-41745**, 221 p.

VACHER, H.L., and HEARTY, P. 1989. History of stage 5 sea level in Bermuda: Review with new evidence of a brief rise to present sea level during substage 5A. Quaternary Science Reviews, **8**: 159-168.

VAUGHAN, T.W. 1919. Fossil corals from Central America, Cuba and Porto Rico, with an account of the American Tertiary, Pleistocene, and Recent coral reefs. United States National Museum Bulletin, **10**: 189-524.

VAUGHAN, T.W., and WELLS, J.W. 1943. Revision of the suborders families, and genera of the Scleractinia. Geological Society of America, Special Paper **14**: 1-363.

WAINWRIGHT, S.A. 1963. Skeletal organization in the coral *Pocillopora damicornis*. Quarterly Journal of Microscopical Science, **104**: 169-183.

WAINWRIGHT, S.A. 1964. Studies of the mineral phase of coral skeleton. Experimental Cell Research, **34**: 213-230.

WARBURTON, F.E. 1958. The manner in which the sponge *Cliona* bores in calcareous objects. Canadian Journal of Zoology, **36**: 555-562.

WARD, W.C. 1970. Diagenesis of Quaternary Eolianites of N.E. Quintana Roo, Mexico. Ph.D. thesis, Rice University, Providence, Rhode Island, 207 p.

WARD, W.C. 1973. Influence of climate on the early diagenesis of carbonate eolianites. Geology, **1**: 171-174.

WARD, W.C. 1975. Petrology and diagenesis of carbonate eolianites of northeastern Yucatan Peninsula, Mexico. *In* Belize Shelf: Carbonate Sediments, Clastic Sediments, and Ecology. *Edited by* K.W. Wantland and W.C. Pusey. American Association of Petroleum Geologists, Studies in Geology **2**: 500-571.

WARDLAW, N., OLDERSHAW, A., and STOUT, M. 1978. Transformation of aragonite to calcite in a marine gasteropod. Canadian Journal of Earth Sciences, **15**: 1861-1866.

WELLS, J.W. 1956. Scleractinia. *In* Treatise on Invertebrate Paleontology. *Edited by* R.C. Moore. Geological Society of America and University of Kansas Press, p. F328-F443.

WINLAND, H.D. 1968. The role of high Mg calcite in the preservation of micrite envelopes and textural features of aragonitic sediments. Journal of Sedimentary Petrology, **38**: 1320-1325.

WOODROFFE, C.D., STODDART, D.R., HARMON, R.S., and SPENCER, T. 1983. Coastal morphology and late Quaternary history, Cayman Islands, West Indies. Quaternary Research, **19**: 64-84.

APPENDIX A

Sampling localities for the Ironshore Formation on Grand Cayman
with locality name and exact location.
UTM = Universal Transverse Mercator

CODE	NAME	UTM - N	UTM - E
ABB	West Bay Coast	2141780	457110
ACB	West Bay Coast	2141800	456800
ACF	West Bay Coast	2141780	456360
ACG	West Bay Coast	2141780	456270
ACH	West Bay Coast	2141890	456100
B		2141040	459820
BTD	Birch Tree - D	2143960	457560
BTH	Birch Tree Hill	2143790	457210
C		2140550	459550
CDS	Cayman Diving School	2132680	459030
CNP	Canal Point	2137550	461450
CYC	Cayman Yacht Club	2140080	460740
D		2140450	459550
DP	Dolphin Point	2141960	455840
DPC	Dolphin Point - C	2142180	455840
DPD	Dolphin Point - D	2142260	455860
DPQ	Dolphin Point Quarry	2142040	455850
E		2141180	459020
EOT	Esso Oil Tanks	2132020	458720
F		2141560	459300
G		2141400	459830
H		2140780	459420
I		2140740	459360
K		2140960	459720
L		2140600	460050
M		2141270	460150
MA	Midland Acres	2133560	476690
MH	Morgan's Harbour	2141920	459620
MHA	Morgan's Harbour - A	2141960	459680
MOA	Middle of Anywhere	2143020	460040
MON	Middle of Nowhere	2143090	460240
MOS	Middle of Somewhere	2143430	460050
NSE	North Sound Estates	2133400	469380
OG	Omega Gardens	2132860	465330
OGA	Omega Gardens - A	2132840	465260
PBQ	Paul Bodden Quarry	2131900	460550

APPENDIX A

Sampling localities for the Ironshore Formation on Grand Cayman
with locality name and exact location.
UTM = Universal Transverse Mercator

CODE	NAME	UTM - N	UTM - E
PSI	Pump Station I	2135780	459700
PWA	Public Works - A	2135380	461280
PWD	Public Works Department	2134920	461680
SBB	Smith's Barcadere - B	2131590	458690
SBD	Smith's Barcadere - D	2131730	458670
SBE	Smith's Barcadere - E	2131820	458630
SBG	Smith's Barcadere - G	2131140	458840
SD	Selkirk Drive	2132510	464360
SDA	Selkirk Drive - A	2132560	464350
SDB	Selkirk Drive - B	2132520	464520
SDC	Selkirk Drive - C	2132600	464720
SHB	Sunset House - B	2132550	458930
TFB	Turtle Farm - B	2143300	456300
TG	Tropical Gardens	2133050	463600
TJU	Prospect Point	2130800	464380
TSE	Tarpon Springs Estates	2134320	478660
U		2136570	460380
VV		2135900	460180
YY		2135180	460140

APPENDIX B

FEIGL'S SOLUTION

PREPARATION

- Dissolve 7.26 g of $MnSO_4 \cdot H_2$ per 100 ml distilled water.
- Add 1 teaspoon Ag_2SO_4
- Heat to a boil (stir frequently), then continue boiling for an additional 2 to 3 minutes.
- Cool to room temperature, then filter out insolubles.
- Add 1 or 2 drops dilute NaOH and stir.
- Let sit 1.5 to 2 hours, then filter out precipitate.

STORAGE AND USAGE

- Store solution in dark bottles, in a cool location. Best results are achieved if the stain is used within 1 week of preparation.
- Prepare a sample for staining by etching with 5% HCl and rinsing thoroughly. Staining time varies with the nature of the sample, therefore check frequently and remove from stain when desired intensity is reached.
- Aragonite is stained black and calcite remains unstained.
- If the sample contains substantial quantities of unconsolidated material, it may be necessary to discard and replace the solution during staining.
- Use extreme caution when staining thin sections as it may obscure features which you may wish to photograph at a later time.